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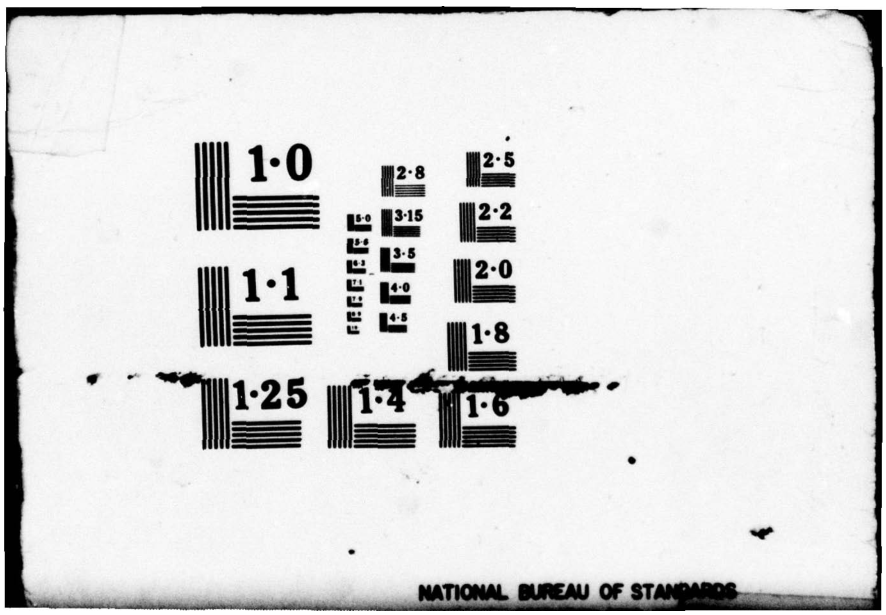
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Fuels Branch
Fuels and Lubrication Division

March 1979

TECHNICAL REPORT AFAPL-TR-79-2019

Final Report for the Period January 1975 to October 1978

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Recent investigations have indicated that aircraft engine exhaust emissions are sensitive to ambient conditions. This paper reports on combustor rig testing intended to evaluate variations due to ambient temperature and pressure with special emphasis on idle engine operating conditions. Empirically determined CO, C_xH_y, and NO_x correction factors--the ratio of the pollutant emission index value obtained during standard day operation to that resulting during actual ambient conditions--are presented. The effects of engine idle cycle pressure

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ratio, primary zone fuel-air ratio, and fuel type were investigated. Ambient temperature variations were seen to cause substantial emission changes; correction factors in excess of 2.0 were determined in some cases. Ambient pressure variations were found to be less substantial. A previously published NO_x emission model and a simplified hydrocarbon combustion analysis are shown to be in general agreement with the empirical results.

FOREWORD

This report contains the results of an effort to evaluate aircraft engine exhaust emissions variations due to ambient temperature and pressure. The key findings of this study were presented at the 1976 ASME Gas Turbine Conference at New Orleans in March and published in ASME Paper 76-GT-130. This report includes a thorough accounting of all results acquired. The work was performed in the Fuels Branch of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project 3048, Task 05, and Work Unit Number 72. The exhaust emissions work was subsequently combined with other combustion activities into Work Unit Number 30480590. The effort represented by this report was managed by W. S. Blazowski and J. W. Marzeski.

The authors wish to express their appreciation to the technicians who skillfully accomplished this project. Combustor rig testing was accomplished by H. Reeves, V. Kelly, and G. Boggs. Exhaust gas analysis was performed by K. Baughman. The authors also wish to acknowledge the engineering support of F. S. Fahrenbruck and S. Stumpf.

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SECTION I

INTRODUCTION

In July of 1973 the US Environmental Protection Agency issued regulations limiting pollutant emissions from future aircraft engines (1). In addition to citing the emission levels to be met, the standards describe detailed procedures for measurement of hydrocarbons (C_xH_y), carbon monoxide (CO), and oxides of nitrogen (NO_x) as well as smoke. These procedures were derived from previous efforts of the E-31 Committee of the Society of Automotive Engineers (2-3). Since the regulations were published, many investigators have attempted to quantify and improve technique accuracy and to reduce costs (4-5).

The emission levels are to be met at "standard day conditions." As they relate to aircraft engine performance requirements, these conditions are defined as 15°C, 0% relative humidity, and 760 mm Hg pressure. Testing seldom occurs at exactly these conditions and methods of correcting for ambient effects on performance are well documented. The meaning of standard day conditions for emission measurement has not yet been established. One key task to be undertaken prior to or along with such a definition is the development of ambient correction factors for pollutant emissions.

The correction factor is defined here as the emission index* for standard day operation divided by that at the actual conditions. There are temperature, pressure, and humidity correction factors (C_T, C_p, and C_H) for each of the

---

* The emission index, which expresses the pollutant emission in terms normalized by fuel (gm pollutant/kg fuel), is used throughout this report. Note that in the case of NO_x the emission index is calculated by accounting for NO and NO_2 as if both species had the molecular weight of NO_2.

three pollutants. Consequently, nine correction factors are necessary for the gaseous emissions data obtained at any single engine operating condition. This definition of the correction factor implies that the product of a measured emission index value with its three correction factors results in the standard day emission index. Interrelationships, especially between temperature and pressure effects, may cause this simplified application to be incorrect. This possibility was not investigated under the program reported herein.

Previous studies (5,6,7) have established that ambient corrections could be substantial. Most of the detailed work to date, however, has concentrated on NO_x emission during high power operation (takeoff and climbout). Both ambient temperature and humidity have been shown to be important in this case. Analytical models have also been employed to predict NO_x correction factors (7,8,9). Figure 1 illustrates the predicted magnitude of high power NO_x emission variation with ambient temperature and humidity.

The purpose of this investigation is the development of emission correction factors for idle operation. A combustor rig facility was employed to simulate the ambient condition effects on combustor inlet temperature and pressure. Because suitable means for adjusting and measuring combustor inlet humidity was not available, this effect was not studied. The possibility that the results obtained might be specific to the experiment performed led to the investigation of a number of additional factors. Simulated compressor pressure ratio was varied over a range consistent with the idle operation of a number of current engines. In addition, combustor airflow was altered to evaluate both rich and lean primary zone operation. Finally, because of the wide usage of both high volatility (JP-4) and low volatility (JP-5 or Jet A) fuels, tests were conducted to uncover any differences due to fuel type.

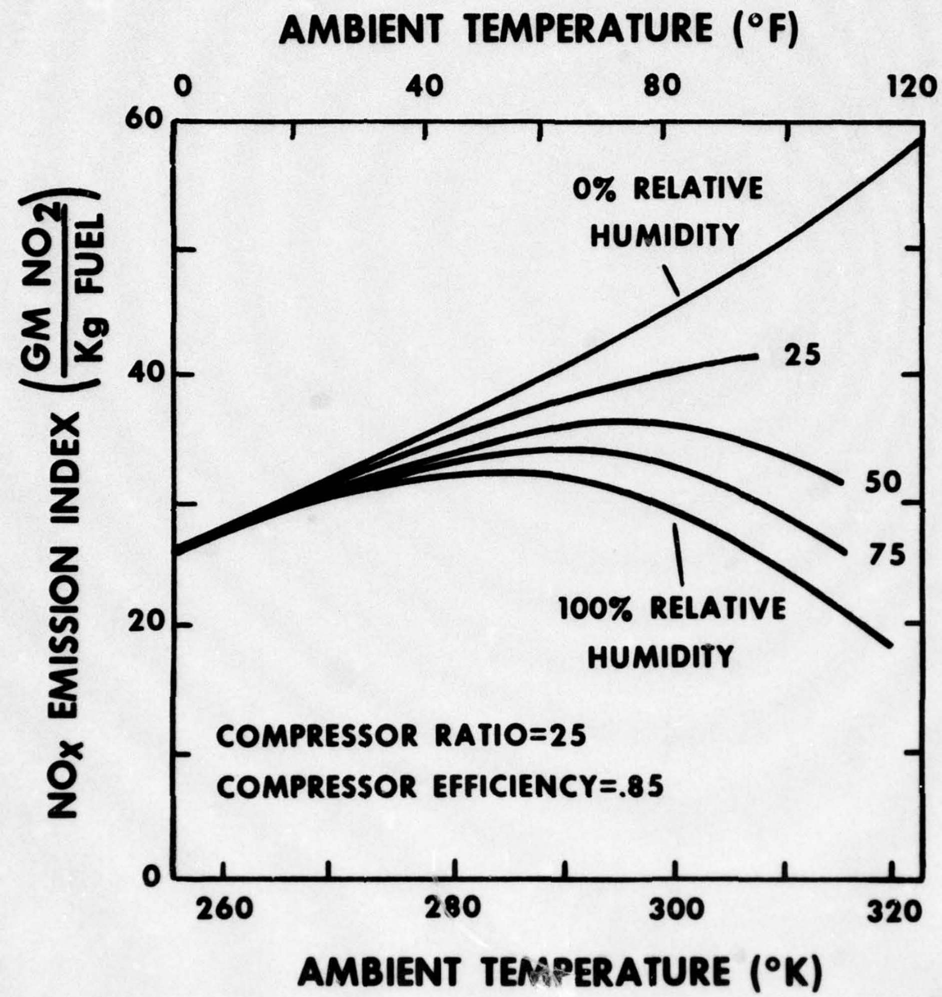

Figure 1. Predicted Ambient Temperature and Humidity Effects on NO_x Emission

Simplified analytical models were also employed to predict ambient variations. Specifically, NO_x idle emission was studied using the analysis described in Reference 7 and a generalized hydrocarbon reaction scheme (10) was used to model C_xH_y emission.

SECTION II

BACKGROUND

The three gaseous pollutants emitted by aircraft gas turbine engines (CO, C_xH_y, and NO_x) can be affected by either ambient temperature, pressure, or humidity. Prior to individually discussing these variations, however, it is necessary to examine the ways in which ambient conditions can affect combustor inlet conditions.

A. Combustor Inlet Conditions

The temperature at the main combustor inlet* can be related to ambient temperature by analyzing the compression process. Figure 2 illustrates the dependence of the combustor inlet temperature on compressor pressure ratio and efficiencies for standard day conditions. Note that at sea-level conditions (of primary interest for emissions measurement) the pressure ratio is identical to the combustor pressure expressed in atmospheres. Compressor efficiency is the ratio of work required for isentropic compression to that for the actual process. Efficiencies of 0.8, 0.85, and 1.0 (isentropic compression) have been indicated. Aircraft engine compressors have efficiencies of about 0.8 at idle and 0.85 at cruise. Idle pressure ratios are between 1.5 and 5.0 while higher power operation utilizes pressure ratios up to 30.

As ambient temperature varies from the 15°C standard day condition, the results of Figure 2 adjust both upward and downward. In the case of engines which are controlled in a manner resulting in approximately constant speed operation at idle, combustor pressure may be assumed to remain constant. By choosing 0.8 as the idle compressor efficiency, the variations in combustor inlet temperature with ambient temperature can be determined. This relation

*Studies of ambient effects on afterburner emissions have not yet been under taken.

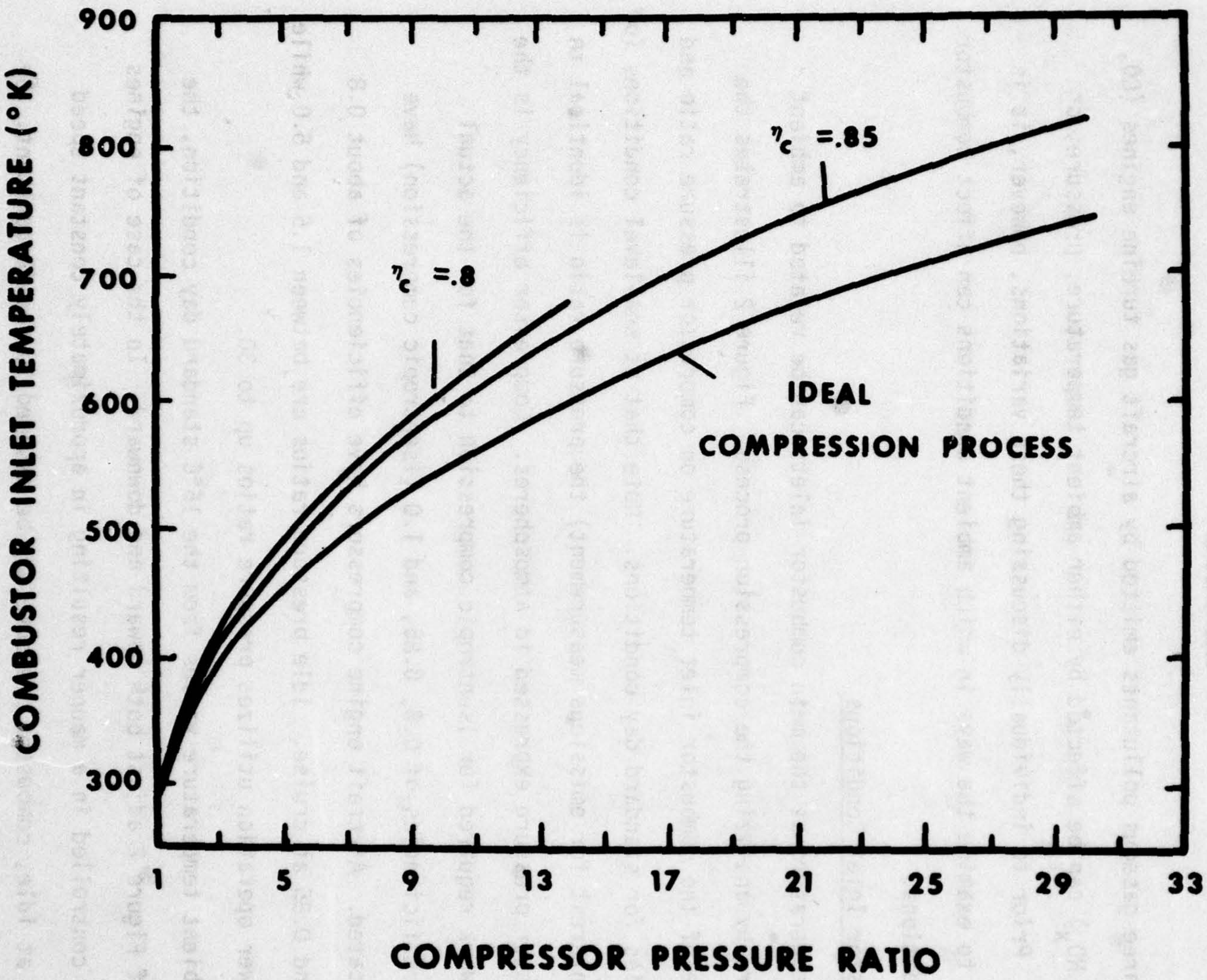

Figure 2. Combustor Inlet Temperature/Pressure Ratio for Standard Day Conditions

is shown in Figure 3. Note that higher dependencies (greater slopes) are associated with the higher pressure ratios.

Since compressor discharge Mach number remains relatively constant with engine speed, combustor air flow will vary with ambient temperature. The variation will be as the inverse square root of the absolute combustor inlet temperature. Combustor fuel air-ratio will vary slightly (<10%) as the fuel control attempts to maintain constant engine speed. Ambient pressure variations have a much more direct effect on combustor inlet conditions. Combustor pressure is directly proportional to the ambient value while combustor inlet temperature is not affected. Airflow is also directly proportional to the ambient pressure. Fuel-air ratio again will vary slightly as constant idle speed is approached. Finally, ambient humidity is assumed to directly affect combustor inlet levels. Changes to the compression process are insignificant and combustor inlet temperature, pressure, and total airflow are not affected.

It should be noted that other engine control systems may cause different relationships between the above parameters. For example, some engines may be controlled to constant corrected speed. These differences would influence the idle correction factors. Consequently, engine control system details are important to correction factor studies.

B. Previous Correction Factor Studies

A number of investigators have attempted to use available engine data to extract information regarding ambient variations. In one case, a large quantity of data (11) was statistically analyzed to extract ambient variations (12). The data were complicated by involving many engine types and a number of organizations participated in the measurement program. Moreover, most of the data were obtained during the warmer months of 1971 and significant ambient variations did not occur in any single measurement location. Consequently, the statistical analysis was not successful in developing correction factors.

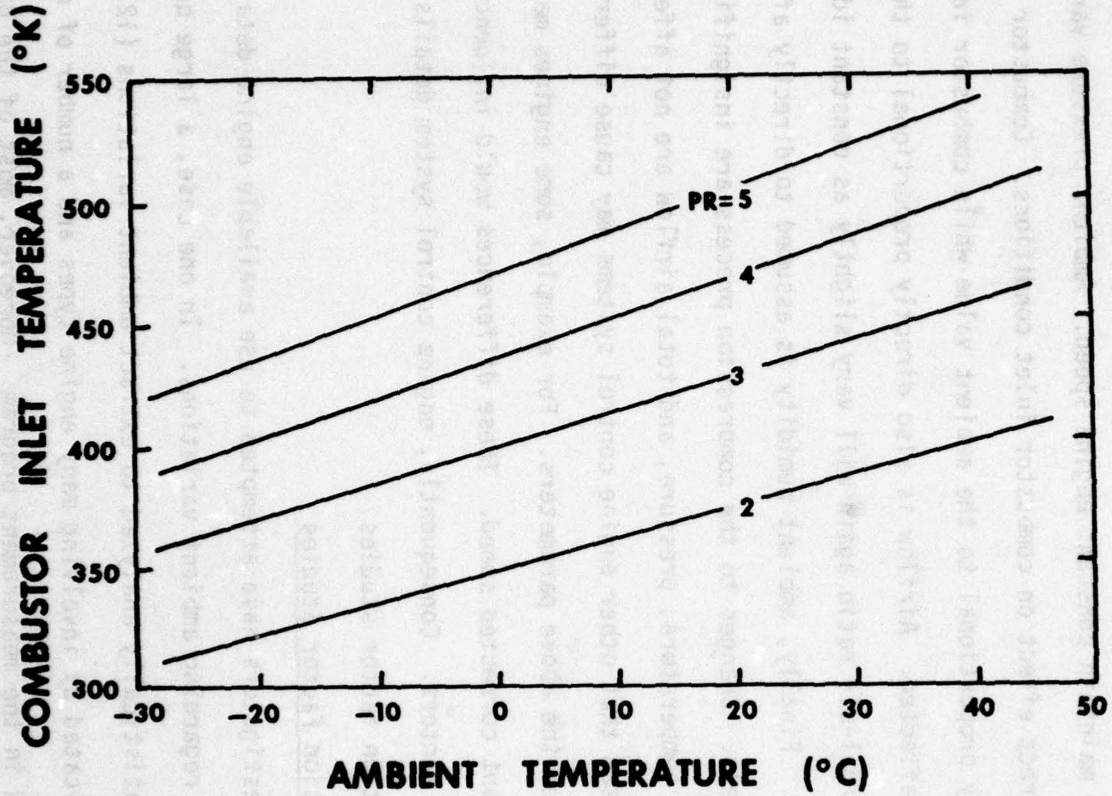

Figure 3. Combustor Inlet Temperature Variation with Ambient Temperature (N_C = 0.8)

More successful efforts have utilized engines dedicated to an ambient effects investigation. Pratt and Whitney engineers have studied a number of engines in this manner (5,13). One difficulty in these data is that the effects of ambient humidity, temperature, and pressure do not occur in a controlled fashion (i.e., two of the variables could not be held constant while the third is varied). Further, extremes of ambient conditions seldom occur at one location within the few month time span usually dedicated to the study. Nevertheless, empirical correlations were established using the data acquired. The Federal Aviation Administration recently completed a similar study examining a number of engines in detail (14).

Combustor rig testing offers the best opportunity to acquire ambient correction factor data in a practical manner. Such a facility allows complete control of combustor conditions to simulate the widest possible ambient condition changes. Further, each ambient variable can be individually investigated. Marchiona (6) studied the effects of humidity on NO_x emission using such an apparatus. A number of others have performed similar studies with the intent of evaluating water or steam injection as a gas turbine NO_x control method.

Analytical modeling to predict ambient effects has been attempted. Studies to date (7,8,9) have concentrated on NO_x emission because of its relatively simple formation mechanism. Results seem to agree well with data. However, careful comparison of the NO_x model results with empirical data has not been extended to idle conditions.

SECTION III

EXPERIMENTAL

A. Facility

The AFAPL Combustion Facility is capable of providing up to 3.4 kg/sec of unvitiated air at pressures up to 18 atm and temperatures up to 450°C. At pressures below 6.5 atm, 9 kg/sec air can be supplied at temperatures up to 570°C. Because intercoolers between air compressor stages effectively remove moisture from the ambient air, combustor inlet air humidity is very nearly zero. Accurate control of combustor pressure and air flow is accomplished by an automatic air bleed control which senses pressure and an exhaust plug which may be remotely operated from the control room. Measurement of air flow is accomplished by the use of a venturi having a 5-cm diameter throat. Fuel flow is determined with a turbine flow metering device. Combustor inlet and exhaust temperatures are measured using chromel-alumel thermocouples.

The single combustors used in this study were T56 Series IIIA combustor cans. The T56 is a turboprop engine used in the C-130 transport aircraft. Six single combustors are arranged in an annular fashion in the engine. This combustor was chosen because of its availability and proven operation in the AFAPL combustor rig system. Although specific combustor inlet pressure, temperature, and mass flow rate apply to T56, these parameters were scaled in this investigation to simulate combustion conditions in other engine types.

Exhaust gases were extracted through a stainless steel probe located approximately ten centimeters behind the combustor exit. The water cooled probe had five equal-sized holes spaced 2.5-cm apart and located horizontally across the combustor exit. The exhaust instrumentation used was as follows: flame ionization detection for total hydrocarbon measurement, chemiluminescent analysis using

an $NO_2 \rightarrow NO$ convertor for NO_x sensing, and nondispersive infrared absorption for CO_2 and CO determination. It is noted that CO_2 concentration was recorded for use in a carbon balance which verified that the sample obtained was representative. Fuel-air ratio calculated from gas analysis is compared to that from fuel and air flow measurement; data are generally not considered acceptable unless the results agree to within $\pm$ 15%.

B. Test Plan

The T56 combustor rig was operated at conditions simulating engine operation at compressor pressure ratios of 2,3,4, and 5 and a constant fuel-air ratio of 0.0078. Standard day inlet temperature conditions were determined from the analysis used to generate Figure 2 assuming a compressor efficiency of 0.8. Air flow was controlled to maintain compressor discharge Mach number at the T56 idle operating value. In effect, this results in rig air mass flow being proportional to $PT^{-1/2}$. Determination of test conditions for simulation of nonstandard day operation required the assumptions discussed in *Section II*. Variations of ambient temperature affected combustor inlet temperature (see Figure 3) without changing combustor pressure. Variations of ambient pressure directly altered combustor pressure without affecting combustor inlet temperature.

JP-4 and Jet A fuels were tested to determine the influence of fuel type on emission variation due to ambient effects. JP-4 is a high-volatility (approximately .2 atm vapor pressure at 40^oC) military fuel, while Jet A is a kerosene based fuel of lower volatility (less than .01 atm vapor pressure at 40^oC) used by U.S. commercial airlines. The flash point* of JP-4 is below -20^oC while that for Jet A is about 50^oC.

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*Temperature at which the equilibrium vapor concentration above an open, one-atmosphere liquid fuel surface reaches the lower flammability limit.

Three combustor configurations were tested to determine the influence of primary zone fuel-air ratio on the correction factor results. The standard T56 design had a primary zone fuel-air ratio of .026. By adjusting primary and downstream airhole sizes in a manner which would maintain the design combustor pressure drop, a "rich combustor" having a primary fuel-air ratio of .038 and a "lean combustor" having a primary fuel-air of .019 were fabricated.

Excessive combustor rig test time precluded the acquisition of data for all permutations of the above-described variables. Determination of temperature and pressure correction factors for all combinations of the four pressures, two fuels, and three combustor configurations would have involved 48 experiments (each including a full variation of ambient temperature or pressure). Required repetition of the data would have further expanded the effort. The twenty-six combinations of conditions selected for the test are shown in Tables 1 & 2. Basically, JP-4 and the standard combustor were used to obtain an extensive quantity of data with other test variables being examined in much less detail.

TABLE 1. AMBIENT TEMPERATURE TEST CONDITIONS

Fuel	Combustor Configuration	Pressure Ratio	No. Repetitions	Figure No.
JP-4	Standard	2	4	A1
JP-4	Standard	3	4	A2
JP-4	Standard	4	4	A3
JP-4	Standard	5	4	A4
JP-4	Lean	2	2	A5
JP-4	Lean	3	2	A6
JP-4	Lean	4	2	A7
JP-4	Lean	5	2	A8
JP-4	Rich	3	2	A9
Jet A	Standard	2	2	A10
Jet A	Standard	3	2	A11
Jet A	Standard	4	2	A12
Jet A	Standard	5	2	A13
Jet A	Lean	2	2	A14
Jet A	Lean	3	2	A15
Jet A	Lean	4	2	A16
Jet A	Lean	5	2	A17

TABLE 2. AMBIENT PRESSURE TEST CONDITIONS

Fuel	Combustor Configuration	Combustor Temp °K	No. Repetitions	Figure No.
JP-4	Standard	366	3	B1
JP-4	Standard	436	3	B2
JP-4	Standard	478	3	B3
JP-4	Standard	505	3	B4
JP-4	Rich	436	3	B5
Jet A	Standard	366	2	B6
Jet A	Standard	436	2	B7
Jet A	Standard	478	2	B8
Jet A	Standard	505	2	B9

SECTION IV

RESULTS

Because a large quantity of data were generated during this program, the main portion of results has been incorporated into Appendices A and B. Tables 1 & 2 list the Figures which correspond to various test conditions. Typical results have been reproduced from the Appendices to aid discussion in this section.

During each test a single complete set of ambient conditions were simulated. The data generated were used to calculate a set of correction factors. These individual results were then analyzed with duplicate sets (in most cases duplicate data were obtained on different test days) to determine a mean correction factor and a standard deviation at each simulated ambient condition. Example results are shown in Figure 4 for C_T and Figure 5 for C_P. The mean $\pm$ one standard deviation is plotted at each ambient condition.

Results for different simulated compressor pressure ratios (Figures A 1 thru A 4) indicate that the ambient temperature correction factor values increase with pressure ratio. This effect is most likely the result of the pressure ratio affecting the slopes of the curves in Figure 3. That is, the increase in combustor inlet temperature for a given increase in ambient temperature is greater for the higher pressure ratios. Further discussion of this effect is offered in Section V.

Although the absolute emissions of CO and C_xH_y for Jet A combustion were signficantly higher than in the case of JP-4, the C_T results are very similar. NO_x correction factors are also nearly identical. Results for the two fuels at the pressure ratio of three condition with the standard combustor can be compared by examining Figures 4 and 6. Other comparisons can be made between Figures A 1 thru A 4 and Figures A 10 thru A 13.

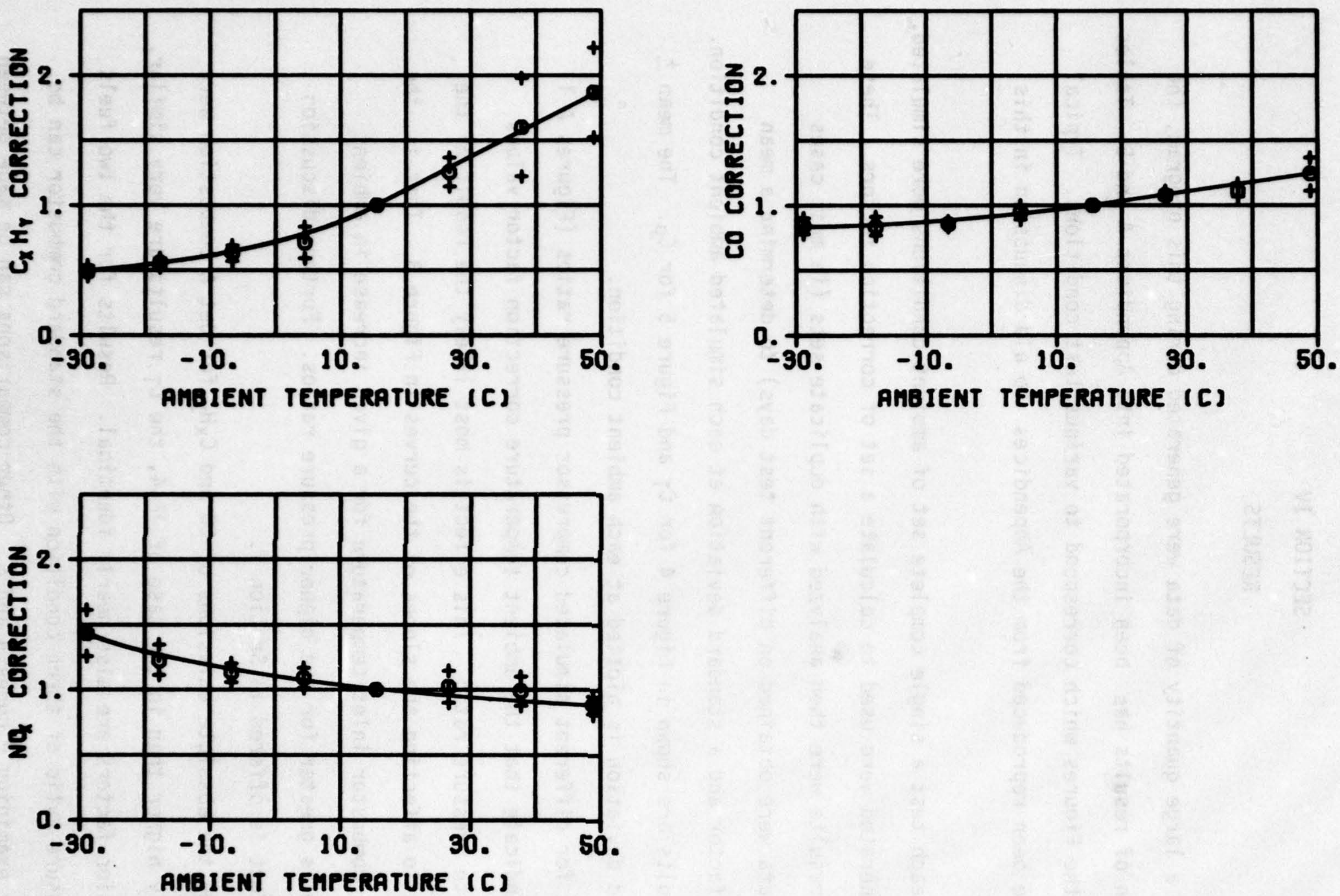

Figure 4. Ambient Temperature Correction Factors for Standard Combustor, PR=3, with JP-4 Fuel

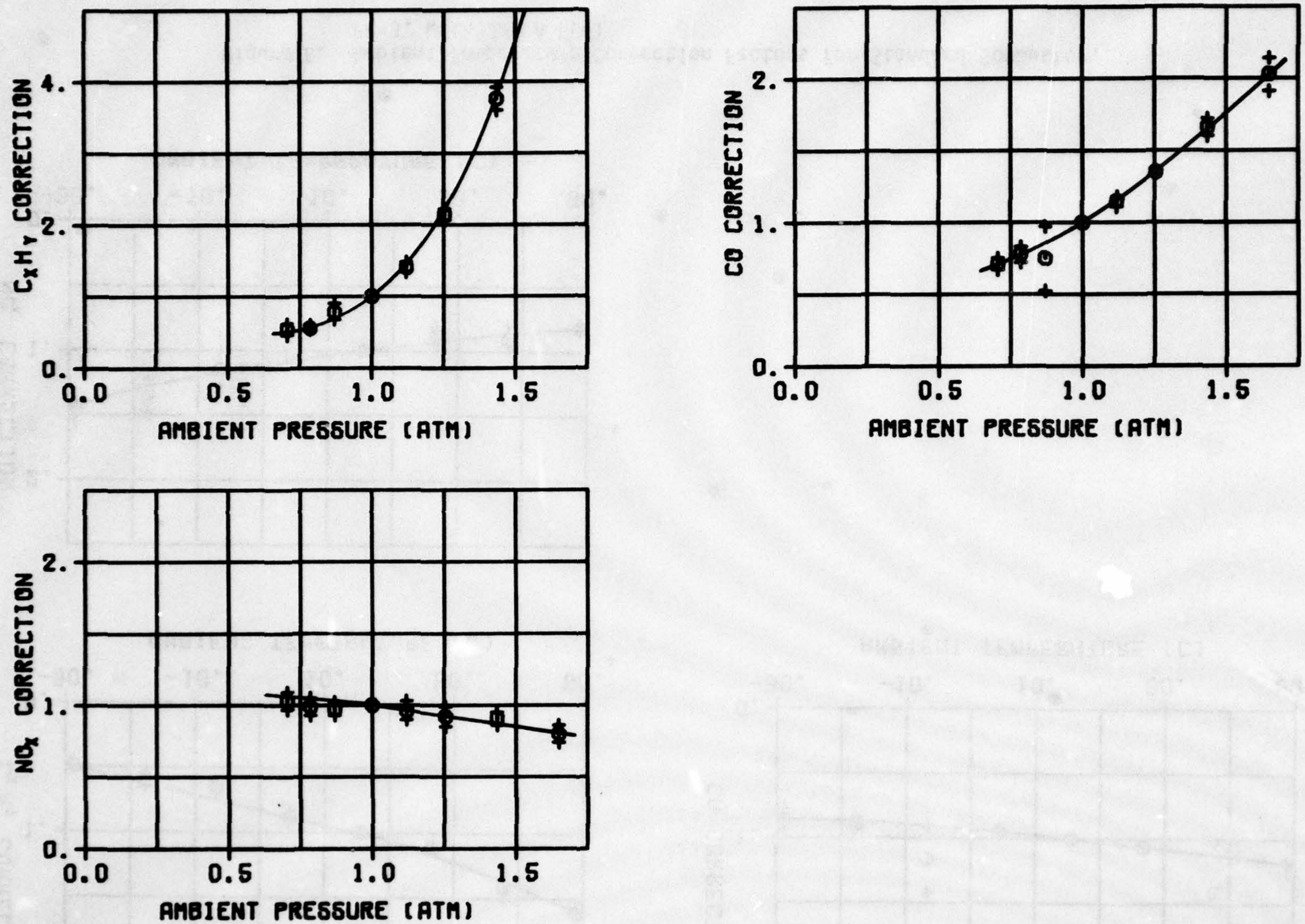

Figure 5. Ambient Pressure Correction Factors for Standard Combustor, $T_3 = 436^oK$, with JP-4 Fuel

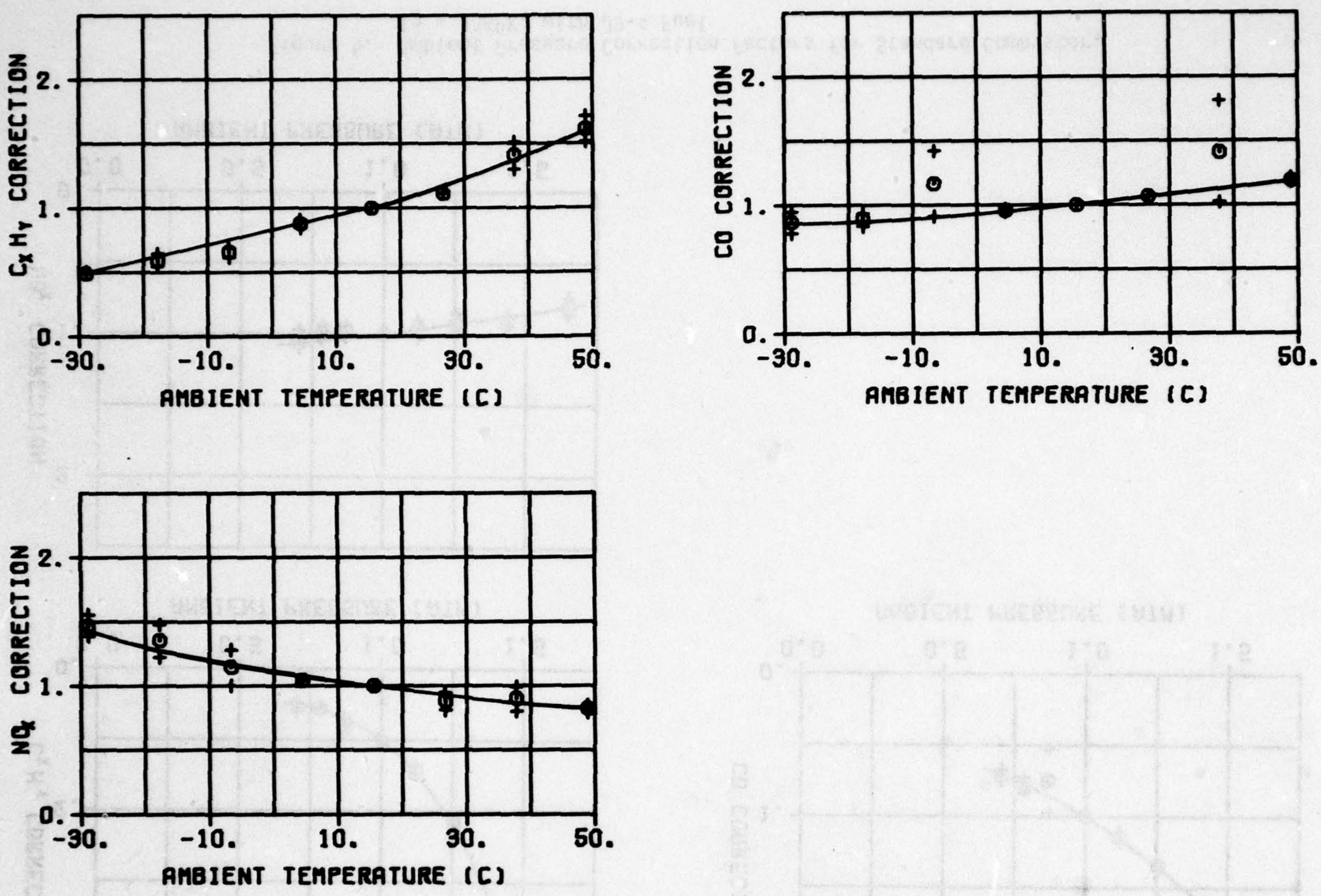

Figure 6. Ambient Temperature Correction Factors for Standard Combustor, PR=3, with Jet A Fuel

C_T results obtained when primary zone fuel-air ratios were varied also indicate surprising similarity. Figures 4 and 7 compare the standard and rich combustor results using JP-4 fuel at the compressor pressure ratio of three condition. It is again noted that the similarity of C_T exists even though the absolute emission index values varied significantly for the two combustors. Figures A1 thru A4 and A5 thru A8 compare the standard and lean combustors.

Figure 5 indicates that C_p values can become quite large for both CO and C_xH_y. However, the large C_p values occur at engine inlet pressures beyond the normal limits of ambient variation. Considering the results for pressures between .90 and 1.05 atmospheres, it is concluded that C_p values are significantly less than typical ambient temperature correction factors. Note that ambient pressure variation arising from test cell limitations (i.e., attempting to obtain sea-level data in an altitude facility) can cause very significant effects. These comments are valid for all pressure correction factors developed as seen in Figures B 1 thru B 9. These results include variations in fuel type, primary zone equivalence ratio, and combustor inlet temperatures.

Finally, some comment regarding data variation is appropriate. At higher ambient temperature conditions, low levels of CO and especially C_xH_y must be measured. This influences the accuracy of the C_T determined as illustrated by the large standard deviations in Figures 4, 6, and 7. This situation also extends to the actual engine emission measurement on a hot day. Consequently, there is a simultaneous reduction in accuracy for the engine measurement and the correction factor employed. Considering the compound effect of these errors, some upper limit on ambient temperature for emission testing may be appropriate.

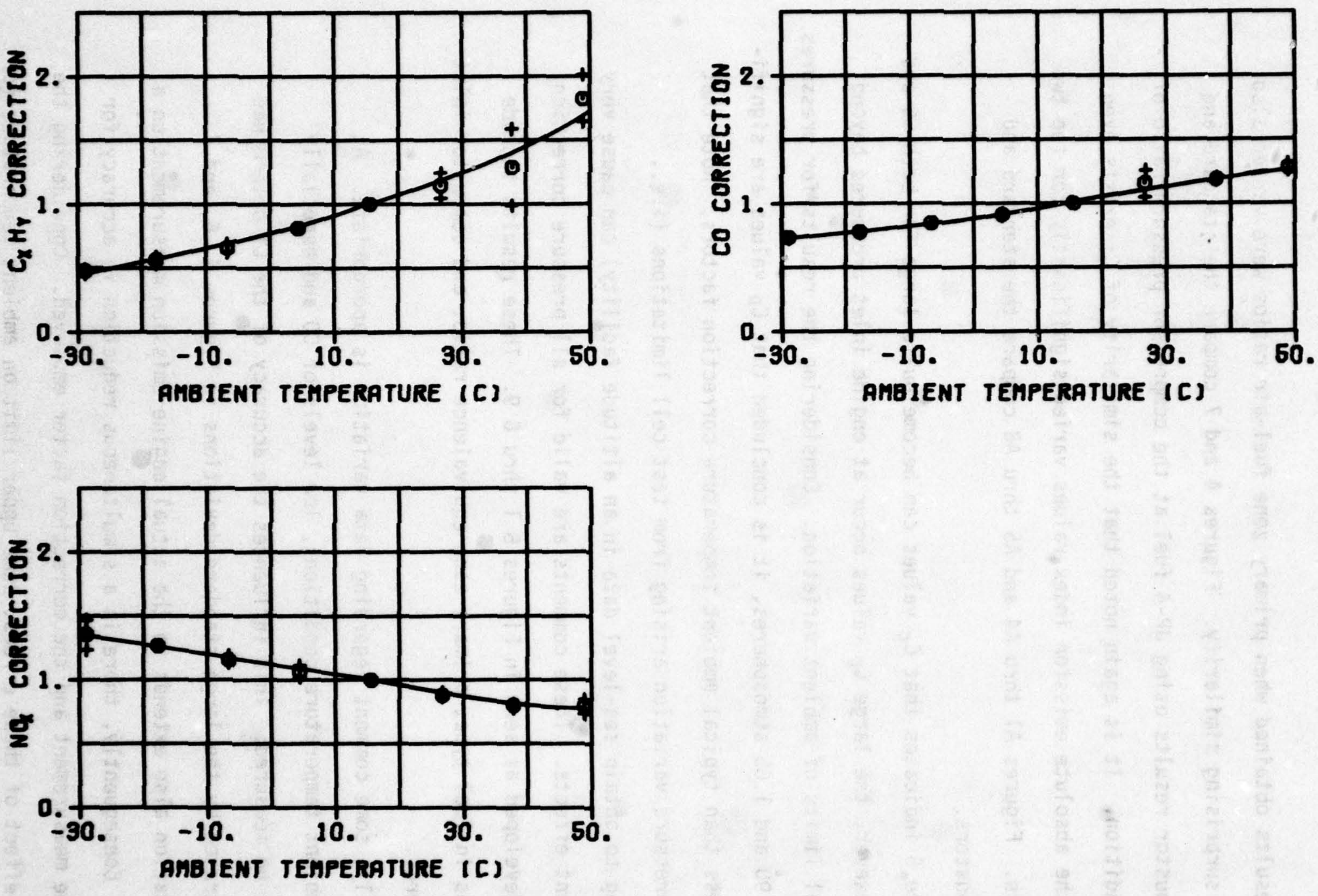

Figure 7. Ambient Temperature Correction Factors for Rich Combustor PR=3, with JP-4 Fuel

SECTION V
ANALYTICAL PREDICTIONS

A. Hydrocarbon Analysis

The temperature effect on hydrocarbon emissions may be investigated using a global reaction model. For this study, the following scheme was used:

$$-\frac{d[C_xH_y]}{dt} = [C_xH_y][O_2]\,T\,C_1 e^{\frac{-E_a}{RT}} \tag{1}$$

where [ ] denotes molar concentration, t is time, T is absolute temperature, C_1 is a constant, and E_a is the reaction activation energy. It is assumed that the reaction occurs predominantly at the maximum combustor temperature. Consequently, T is taken as the flame temperature, T_f. It is further assumed that reaction takes place at the rate corresponding to T_f for a time t_{res}. Finally, $[O_2]$ is assumed to change according to density variation only. That is, $[O_2] = C_2\,(P_3/T_f)$, where P_3 is the absolute combustor pressure. Equation 1 becomes:

$$\ln\left(\frac{[C_xH_y]\ \text{initial}}{[C_xH_y]\ \text{final}}\right) = C_1C_2\left(\frac{P_3T_f}{T_f}\right) t_{res} e^{\frac{-E_a}{RT_f}} \tag{2}$$

The residence time, t_{res}, is inversely proportional to combustor velocity. Because of the constant Mach number characteristic mentioned in Section II, t_{res} is assumed to be proportional to $(T_3)^{-1/2}$, where T_3 is the absolute combustor inlet temperature. Equation 2 becomes:

$$\frac{(T_3)^{1/2}}{P_3}\ln\left(\frac{[C_xH_y]\ \text{initial}}{[C_xH_y]\ \text{final}}\right) = C_3 e^{\frac{-E_a}{RT_f}} \tag{3}$$

The temperature correction factor data described in Section IV may be examined using this equation. Specifically, the results for the standard T56

combustor using JP-4 fuel were studied. T_f was determined for each of the inlet pressures and temperatures tested using a constant pressure adiabatic flame temperature program (15). The equivalence ratio corresponding to the primary zone value of the standard T56 configuration (see Section IIIB) was used in the calculation. Experimental hydrocarbon emission values were used to calculate $[C_xH_y]_{final}$ and the known primary zone fuel-air ratio was used to determine $[C_xH_y]_{initial}$. Results are shown in Figure 8.

Equation 3 illustrates that the semi-log plot of Figure 8 is similar to an Arrhenius plot and a constant slope of data plotted would allow E_a to be determined. Figure 8 indicates four linear sets of data corresponding to the different inlet pressures studied. The values of E_a calculated from the least-square fits are indicated. E_a results for the different pressures compare favorably. These values are also in reasonable agreement with that given by Edelman, et. al. (10) for the hydrocarbon disappearance reaction, 22.4 kcal/g mole. This is an encouraging result which indicates a possible means of predicting ambient temperature correction factors for hydrocarbons.

Equation 3 has been used to develop ambient temperature correction factors. Data obtained for the standard day condition for each pressure ratio were used to calculate C_3 values. This allowed $[C_xH_y]_{initial}/[C_xH_y]_{final}$ and, finally, the ambient temperature correction factors to be calculated. The results, which are in good agreement with the combustor rig data, are shown in Figure 9. The drawback of this procedure is that the primary zone equivalence ratio and the standard day emission concentration must be known or approximated. The estimate of standard day emission need only be within a factor of two for approximate calculation ($\pm$20%) of the correction factor.

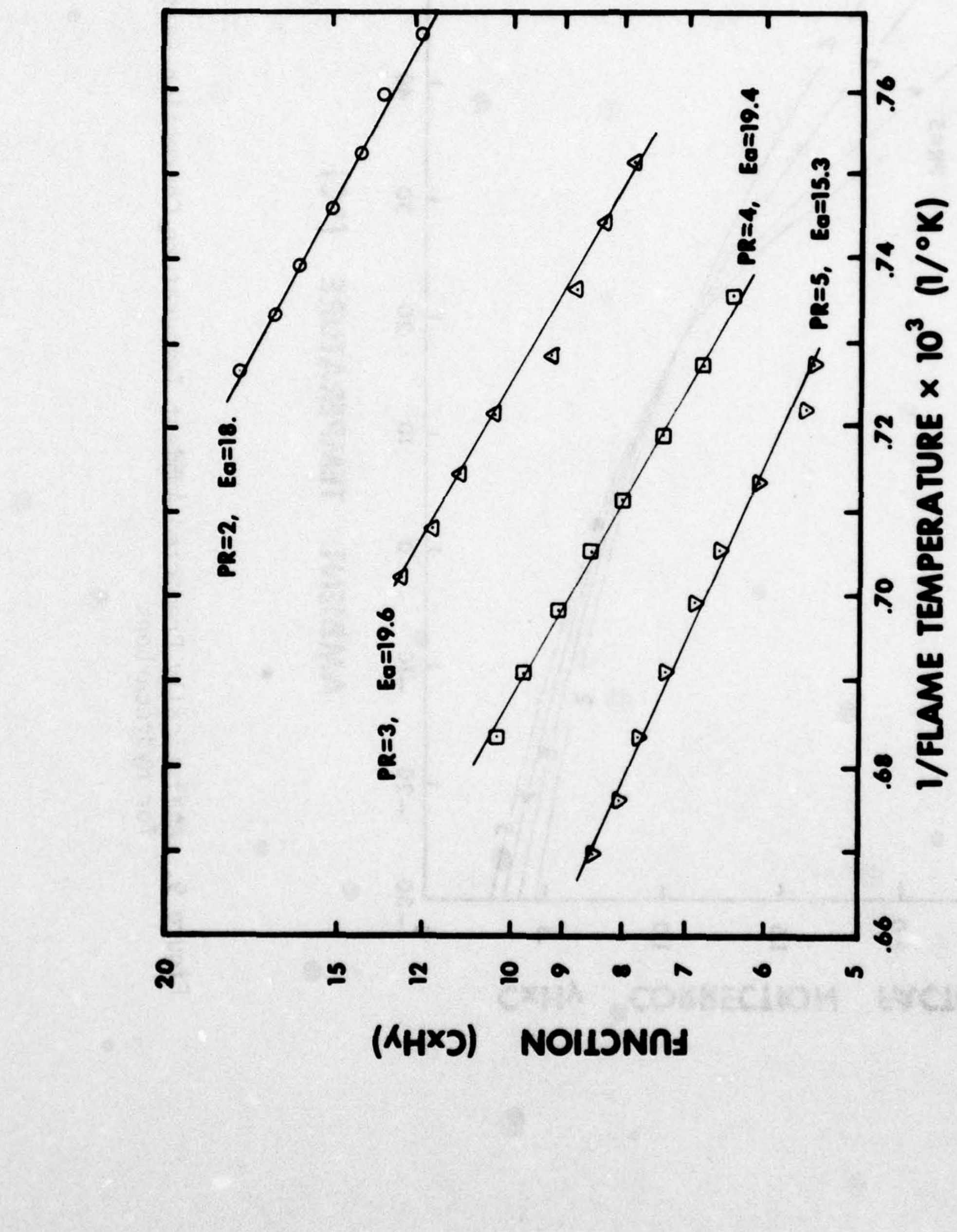

Figure 8. Hydrocarbon Data Correlation

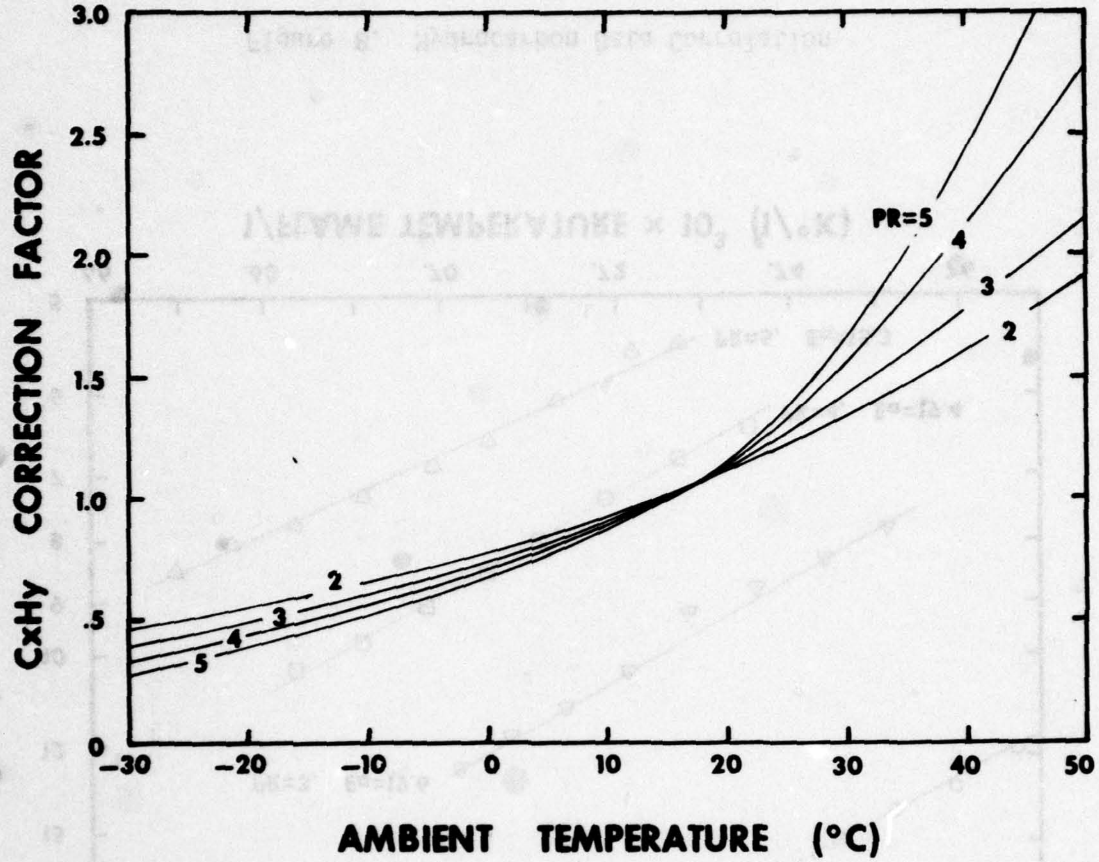

Figure 9. Analytically Predicted Ambient Temperature Correction Factors for Hydrocarbons

B. CO Analysis

Similar attempts to develop a simplified model of the processes affecting CO emission were unsuccessful. Such an analysis must necessarily be more complex because, unlike C_xH_y and NO_x, CO in the combustion zone is significantly affected by both production and consumption reactions. More sophisticated analyses should be used to attempt prediction of CO ambient variations. Models like that described in Reference 16 consider the necessary chemical kinetic processes.

C. NO_x Analysis

Predictions of the NO_x model described in Reference 7 were compared with the data. This model assumes NO_x is formed by the Zeldovitch mechanism at flame temperatures corresponding to $\phi = 0.9$ and prompt NO formation is included in the analysis. More than 50% of idle NO_x emissions are predicted to be formed by the prompt NO mechanism.

Figure 10 is a comparison of the analysis with the data. Reasonably favorable agreement was obtained. However, the data indicate that combustion efficiency variations at idle may have affected the NO_x formation process. While the model assumes full achievement of the adiabatic flame temperature, the data may have been affected by substantially lower combustion efficiency as ambient temperature decreases were simulated. In this case, the model would be expected to under-predict the correction. Figure 10 indicates a trend toward this situation. Consequently, models to accurately predict ambient temperature effects on idle NO_x emission may be required to be more sophisticated than those for high power conditions where 100% combustion efficiency is a valid assumption.

Ambient pressure effects are well predicted by the model. The $P^{-1/2}$ correction (see Section II) is a suitable means of treating these variations. Note that over the normal range of ambient variation the pressure correction is small in comparison with the temperature effect.

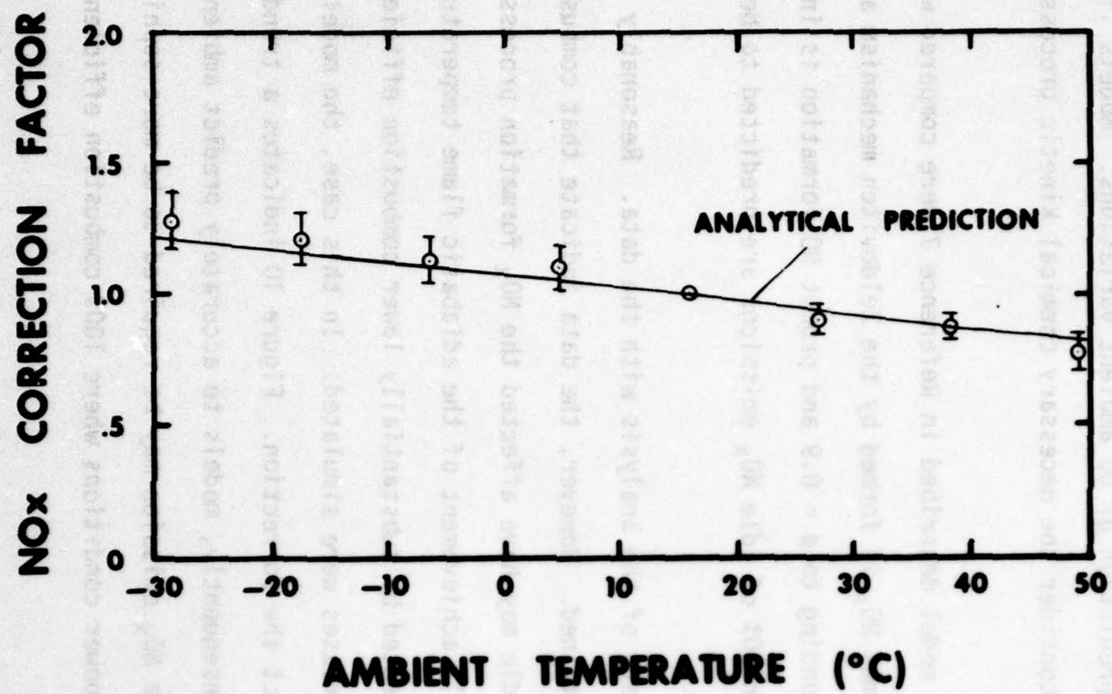

Figure 10. Comparison of Empirical NO_x, Ambient Temperature Correction with Analytical Prediction

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Ambient temperature and pressure correction factors for idle operation have been studied using a T56 single combustor rig. Simplified models of pollutant chemistry have also been attempted. Results of these efforts have indicated the following:

a. Hydrocarbon emissions are very significantly affected by ambient temperature variation. Correction factors exceeding 2.0 were determined in a number of cases. NO_x and CO have less substantial dependence on ambient temperature.

b. Over the normal range of ambient variation, the pressure correction is small in comparison with the temperature effect. Engine inlet pressure variations experienced in test cell operation not properly simulating sea-level conditions, however, can cause significant effects.

c. Compressor pressure ratio was found to significantly affect correction factors in each case. Engines with higher idle pressure ratio require more correction for the same nonstandard-day condition.

d. Although variations in fuel type (JP-4 versus Jet A) and primary zone equivalence ratio significantly altered absolute C_xH_y and CO emission levels, the correction factor results obtained were not affected.

e. Efforts to determine correction factors by using simplified analytical models were fairly successful. A global reaction model of hydrocarbon consumption led to prediction of C_xH_y correction factors which compared favorably with the data. A previously published model for NO_x prediction was in fair agreement with the empirical results. It was postulated, however, that consideration of combustion efficiency variations may be necessary for accurate prediction of idle NO_x variation. Attempts to predict CO variations were unsuccessful.

These results must not be considered as universally applicable. The T56 combustor was the only design tested and, although primary zone equivalence ratio variations did not affect these results, other designs may behave differently. Further, the underlying assumptions of combustor inlet condition response to ambient variations (constant combustor pressure for ambient temperature variations and constant inlet temperature for ambient pressure variation) are not appropriate for engines controlled to other than constant speed.

Three general recommendations can now be made. First, additional combustor design types should be studied. In particular, these should include air blast fuel injection designs and combustors intended to meet the 1979 EPA standards. Secondly, more sophisticated analytical modeling should be pursued as a means of developing correction factors. The payoff of such an effort could be relatively inexpensive calculation of correction factors once combustor design parameters have been established. Finally, ambient humidity variation, which was not studied during this effort, should be investigated. Previous efforts (see Section II) have indicated that this variation can be as significant as the ambient temperature effect.

APPENDIX A

AMBIENT TEMPERATURE CORRECTION FACTORS

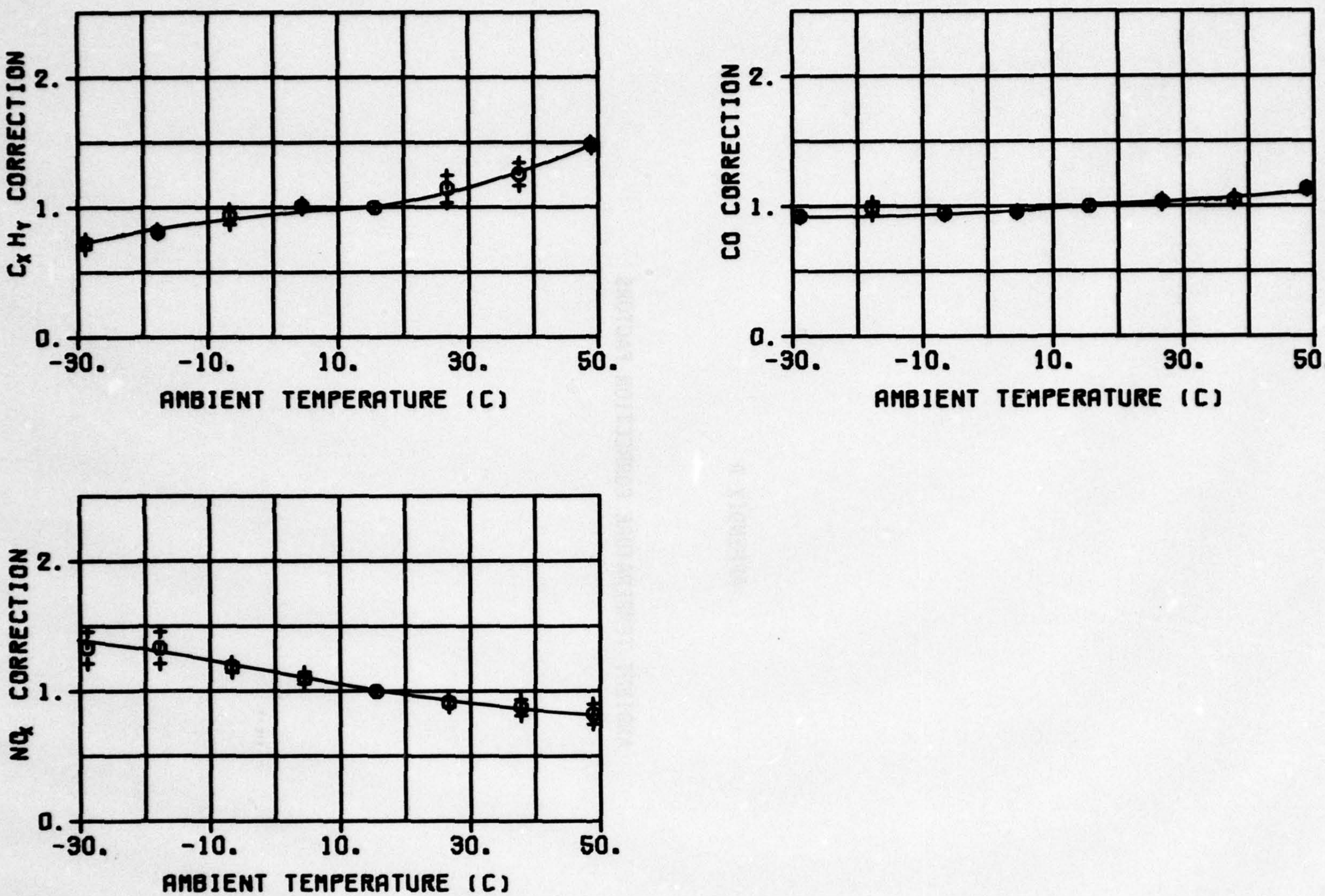

Figure A 1 Ambient Temperature Correction Factors for Standard Combustor, PR=2, with JP-4 Fuel

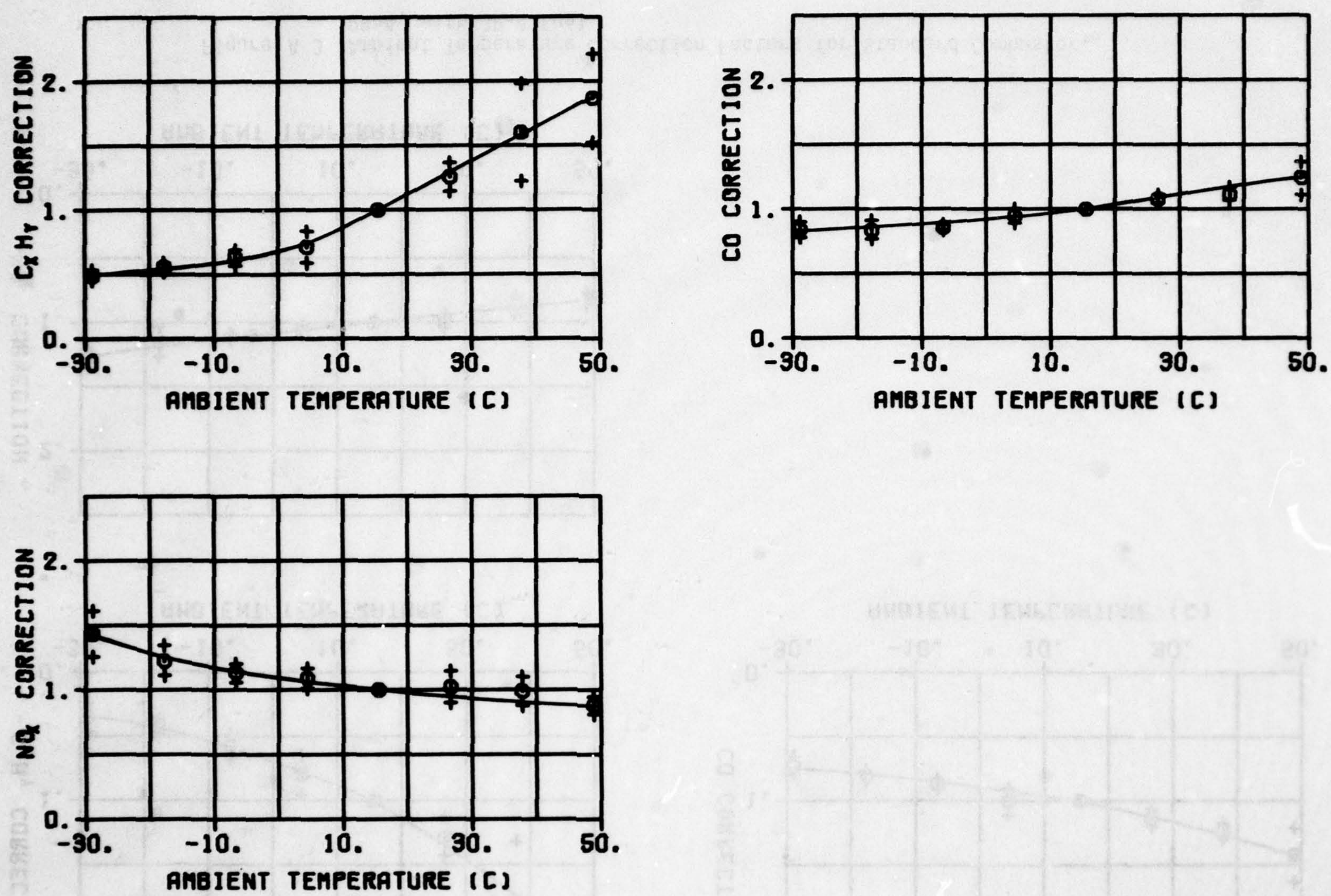

Figure A 2 Ambient Temperature Correction Factors for Standard Combustor, PR=3. with JP-4 Fuel

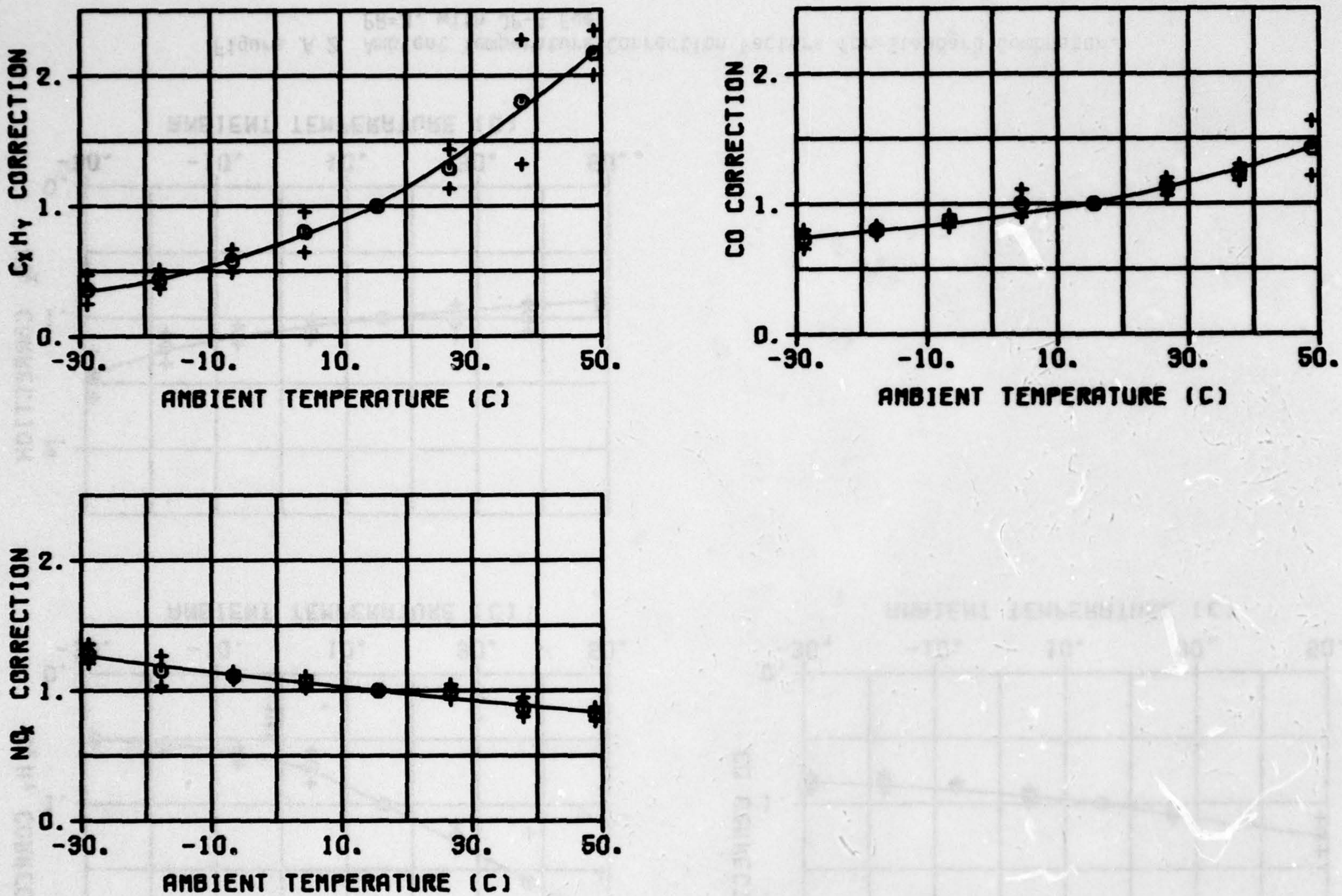

Figure A 3 Ambient Temperature Correction Factors for Standard Combustor, PR=4, with JP-4 Fuel

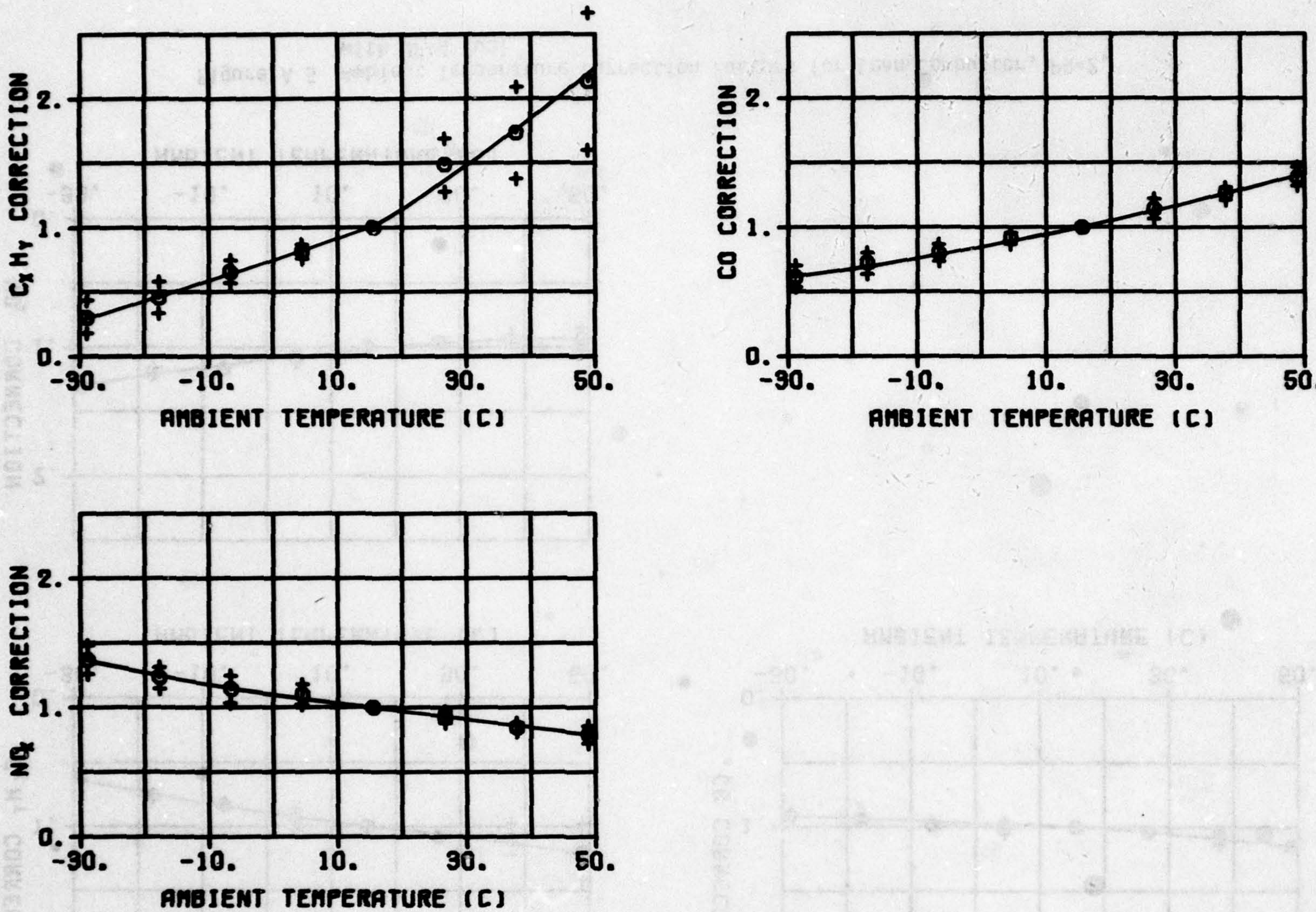

Figure A 4 Ambient Temperature Correction Factors for Standard Combustor, PR=5, with JP-4 Fuel

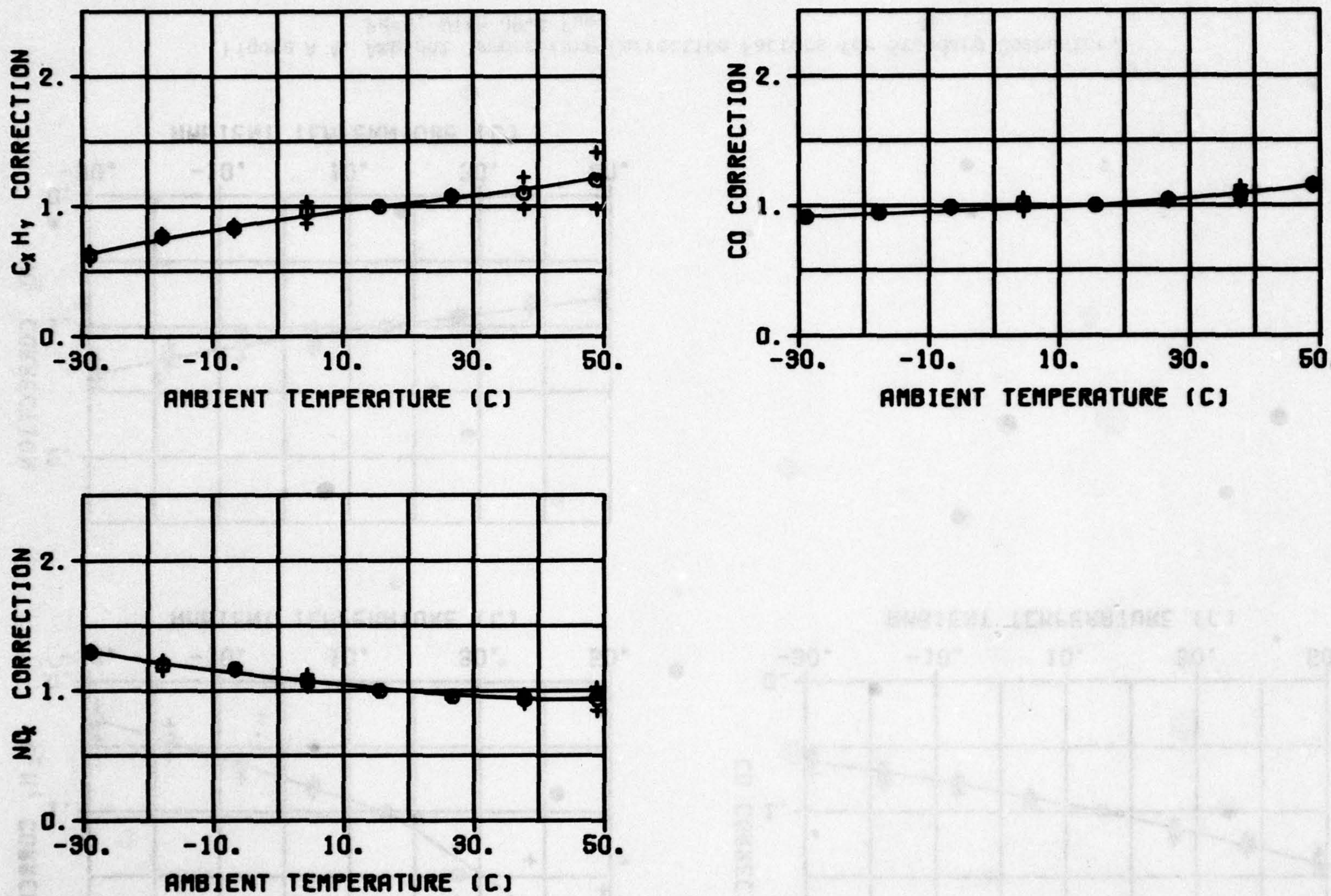

Figure A 5 Ambient Temperature Correction Factors for Lean Combustor, PR=2, with JP-4 Fuel

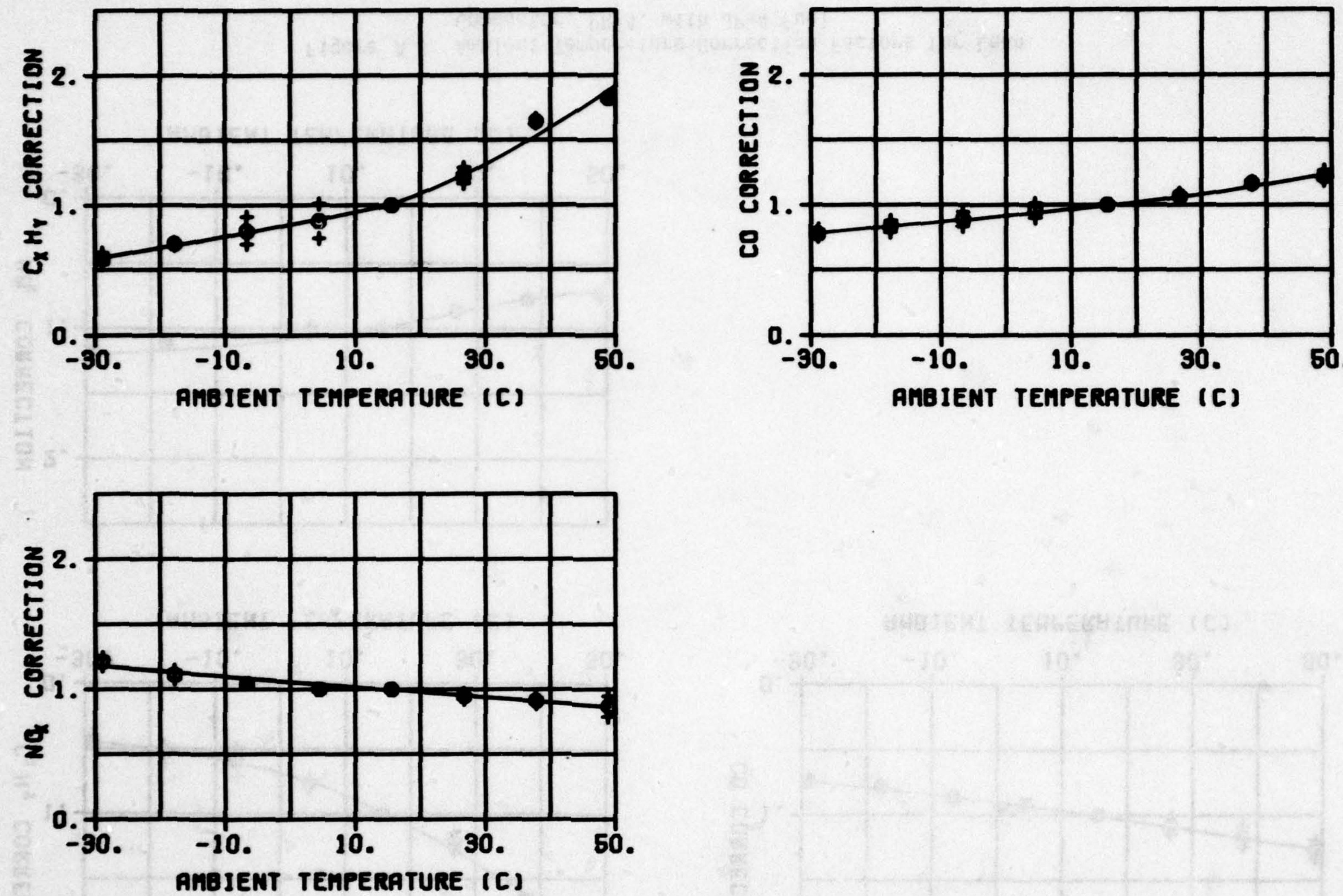

Figure A 6 Ambient Temperature Correction Factors for Lean Combustor, PR=3, with JP-4 Fuel

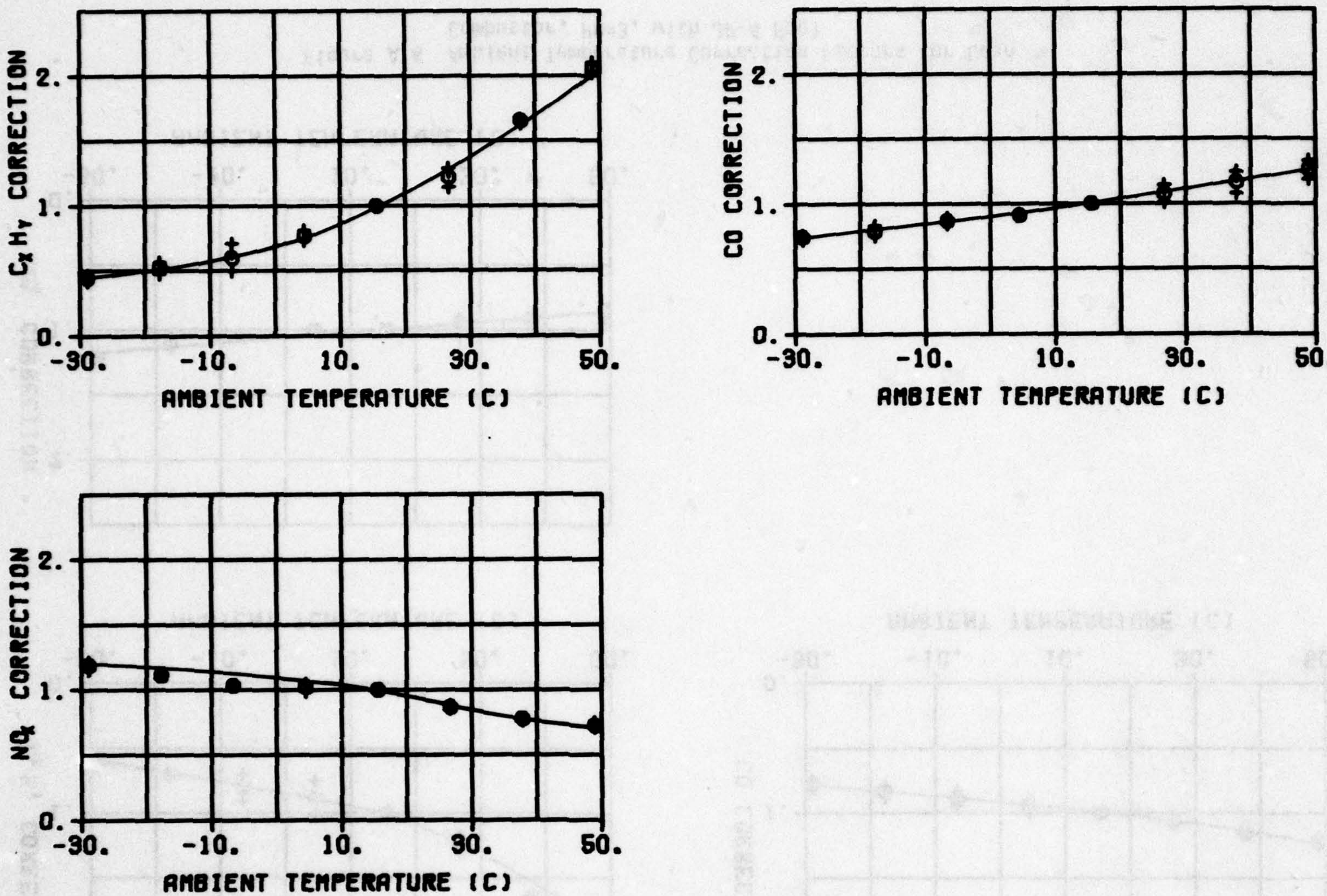

Figure A 7 Ambient Temperature Correction Factors for Lean Combustor, PR=4, with JP-4 Fuel

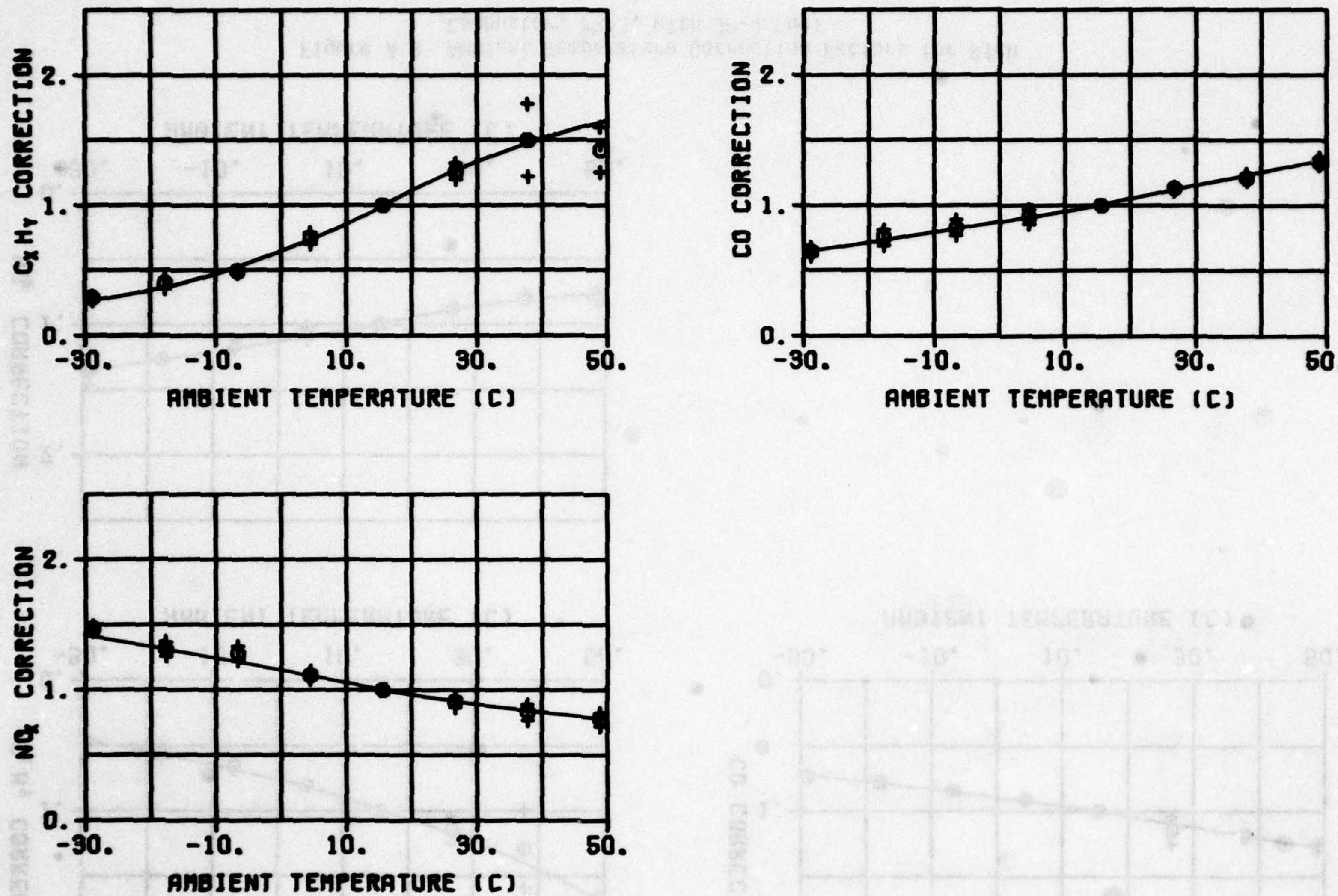

Figure A 8 Ambient Temperature Correction Factors for Lean Combustor, PR=5, with JP-4 Fuel

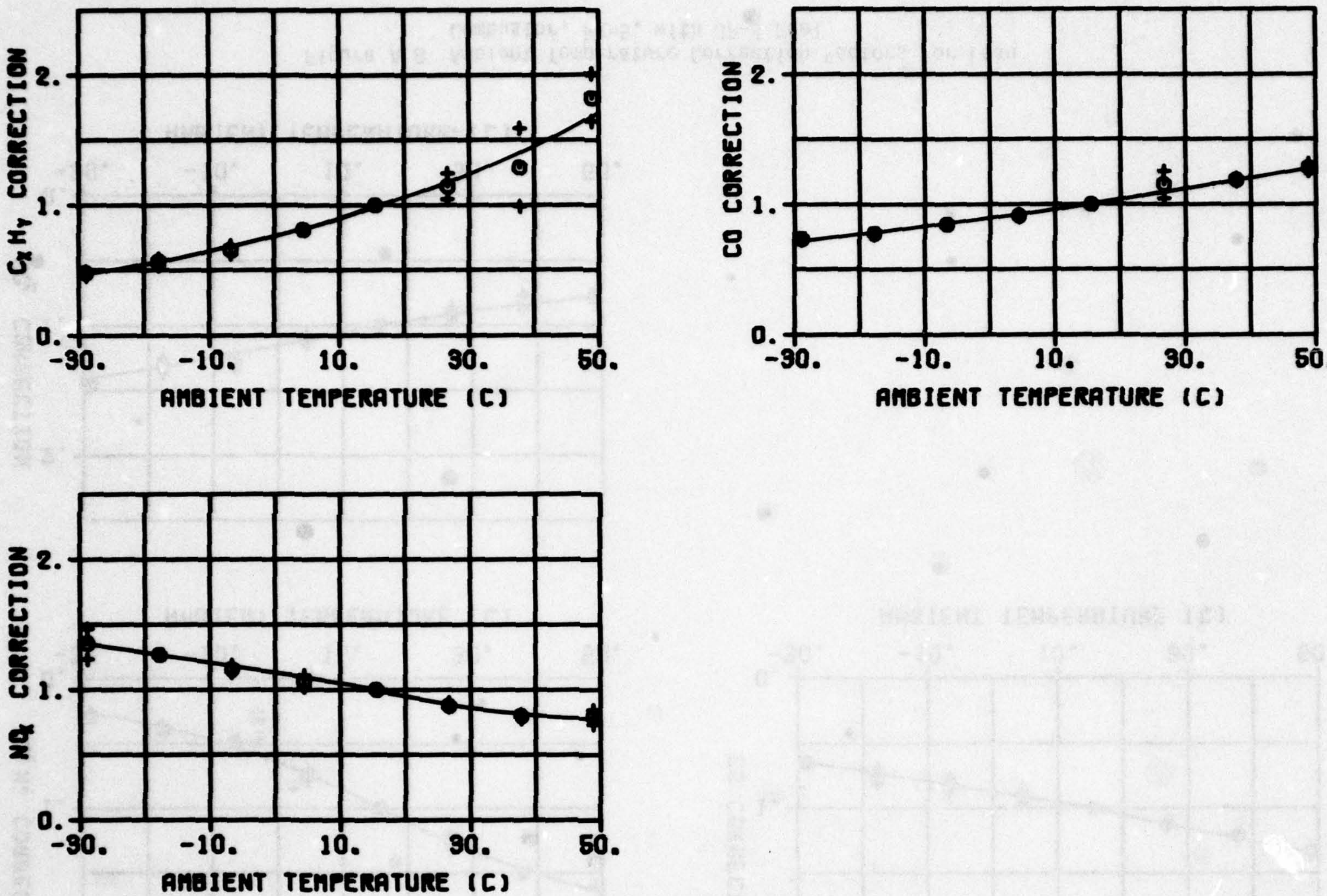

Figure A 9 Ambient Temperature Correction Factors for Rich Combustor, PR=3, with JP-4 Fuel

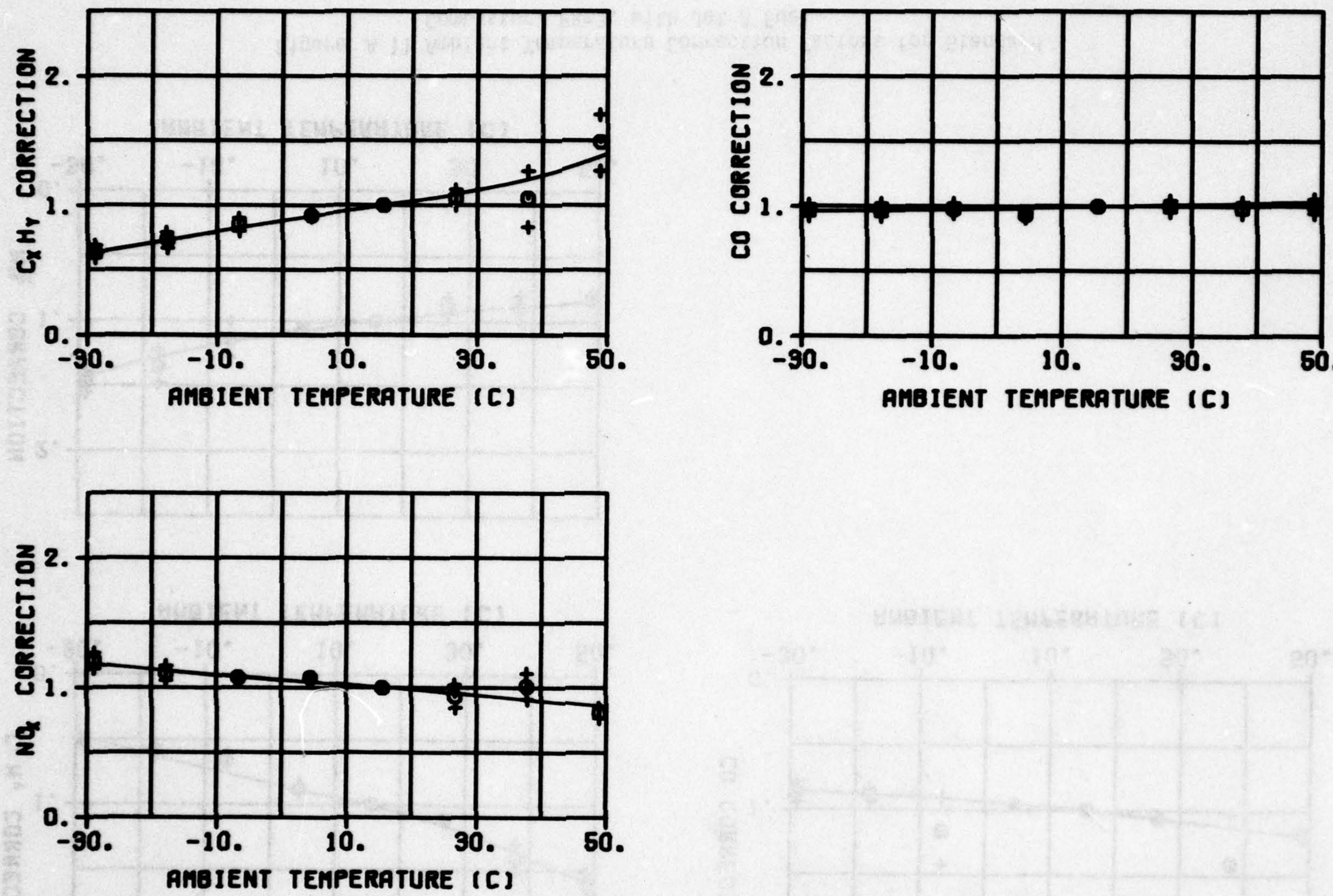

Figure A 10 Ambient Temperature Correction Factors for Standard Combustor, PR=2, with Jet A Fuel

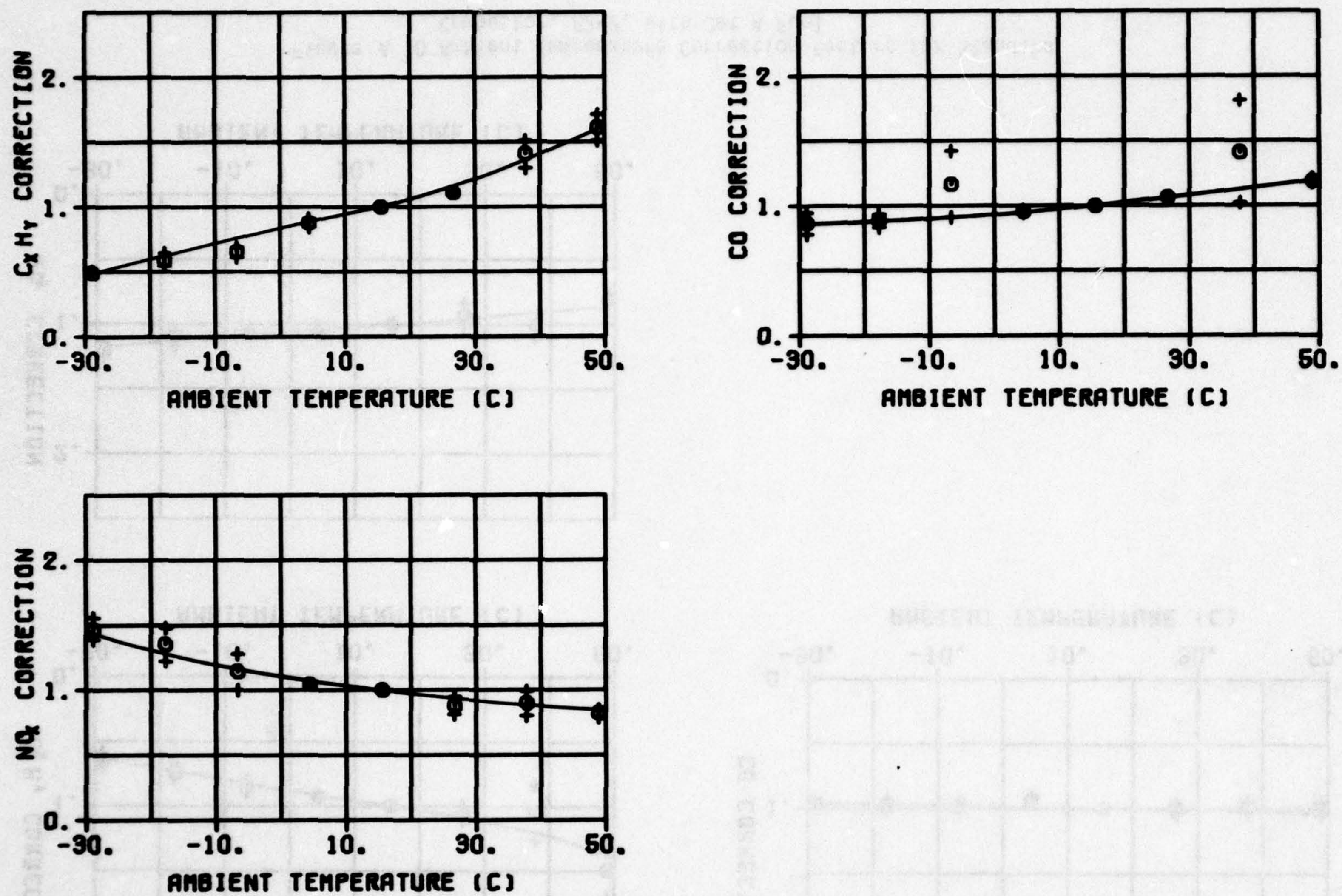

Figure A 11 Ambient Temperature Correction Factors for Standard Combustor, PR=3, with Jet A Fuel

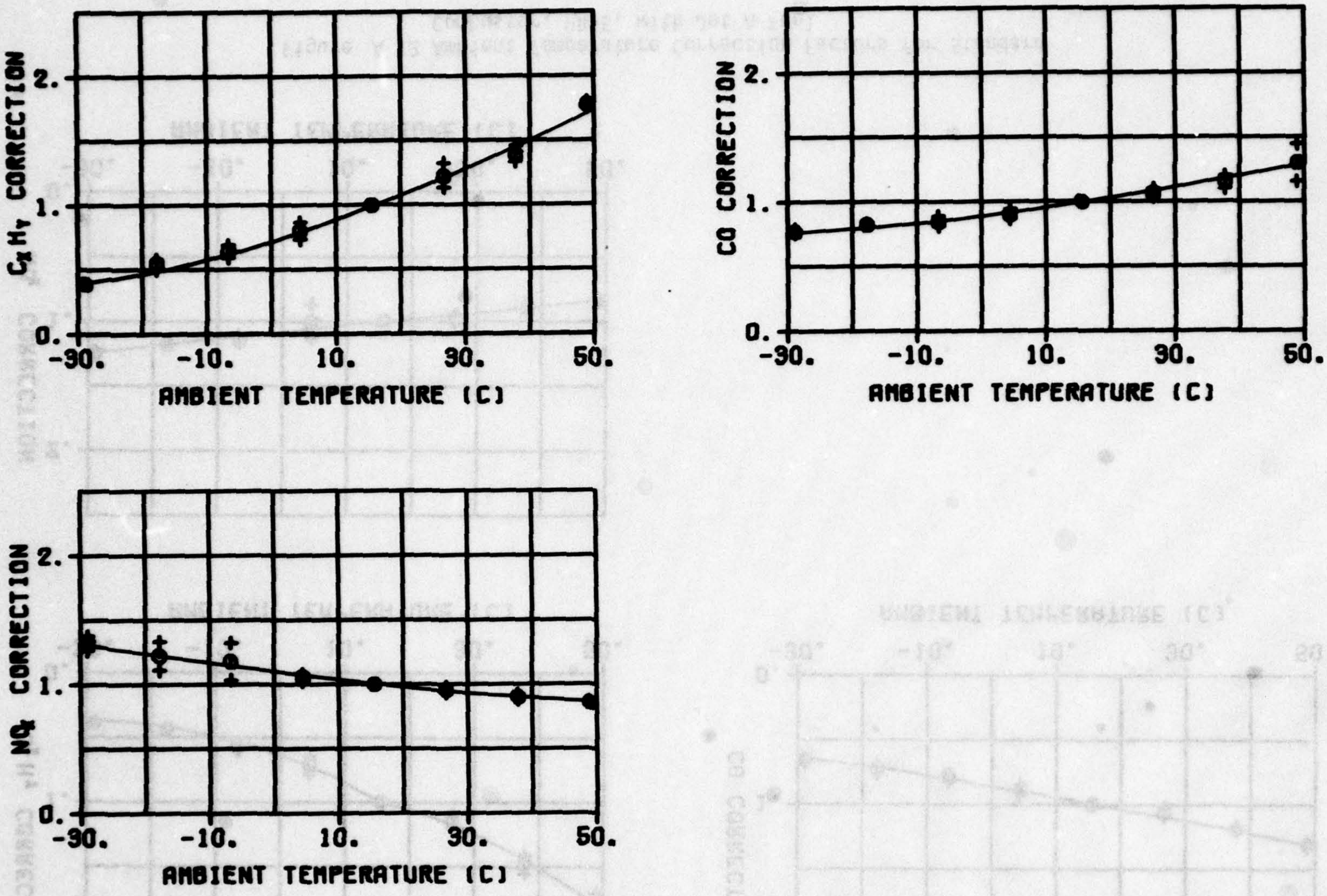

Figure A 12 Ambient Temperature Correction Factors for Standard Combustor, PR=4, with Jet A Fuel

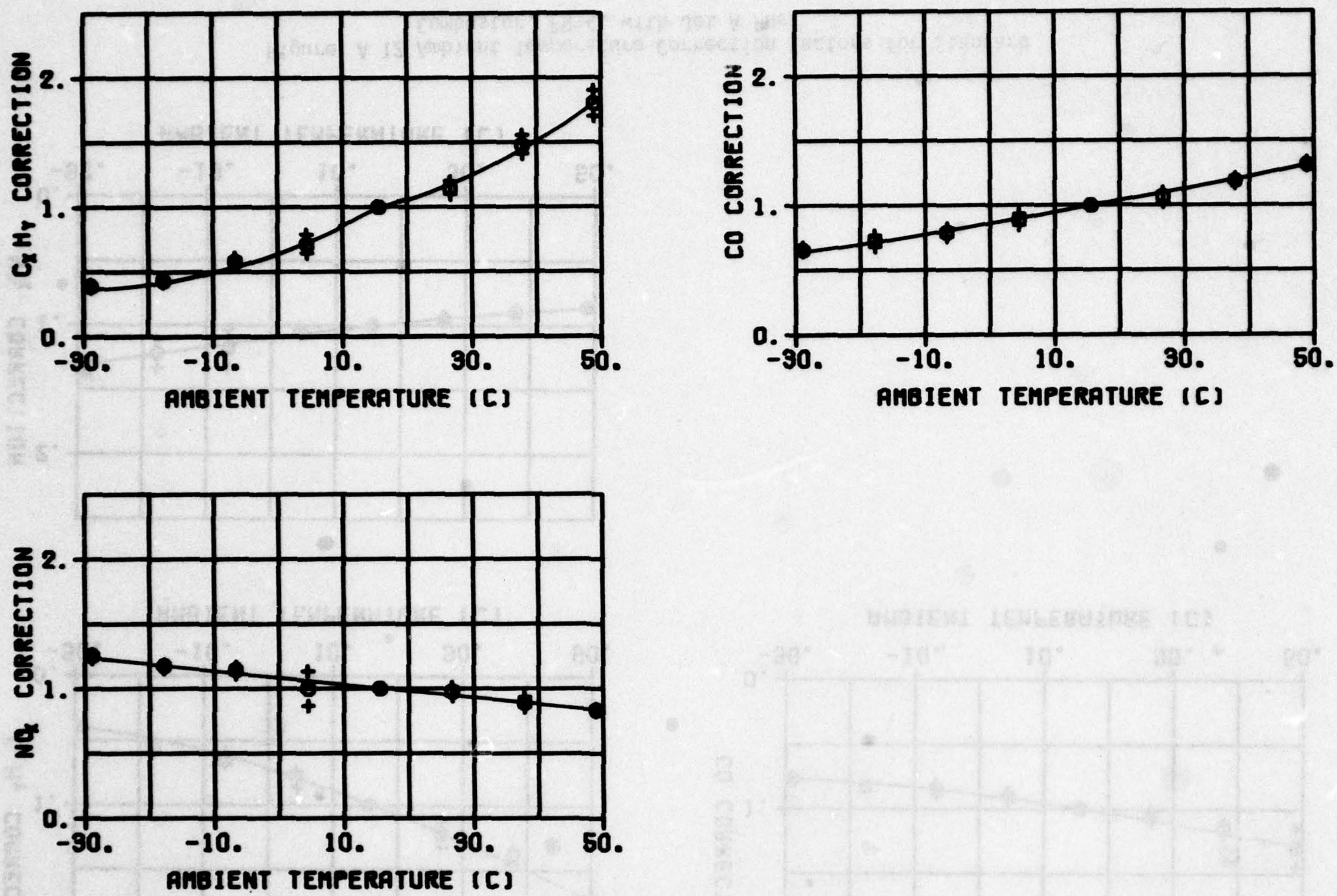

Figure A 13 Ambient Temperature Correction Factors for Standard Combustor, PR=5, with Jet A Fuel

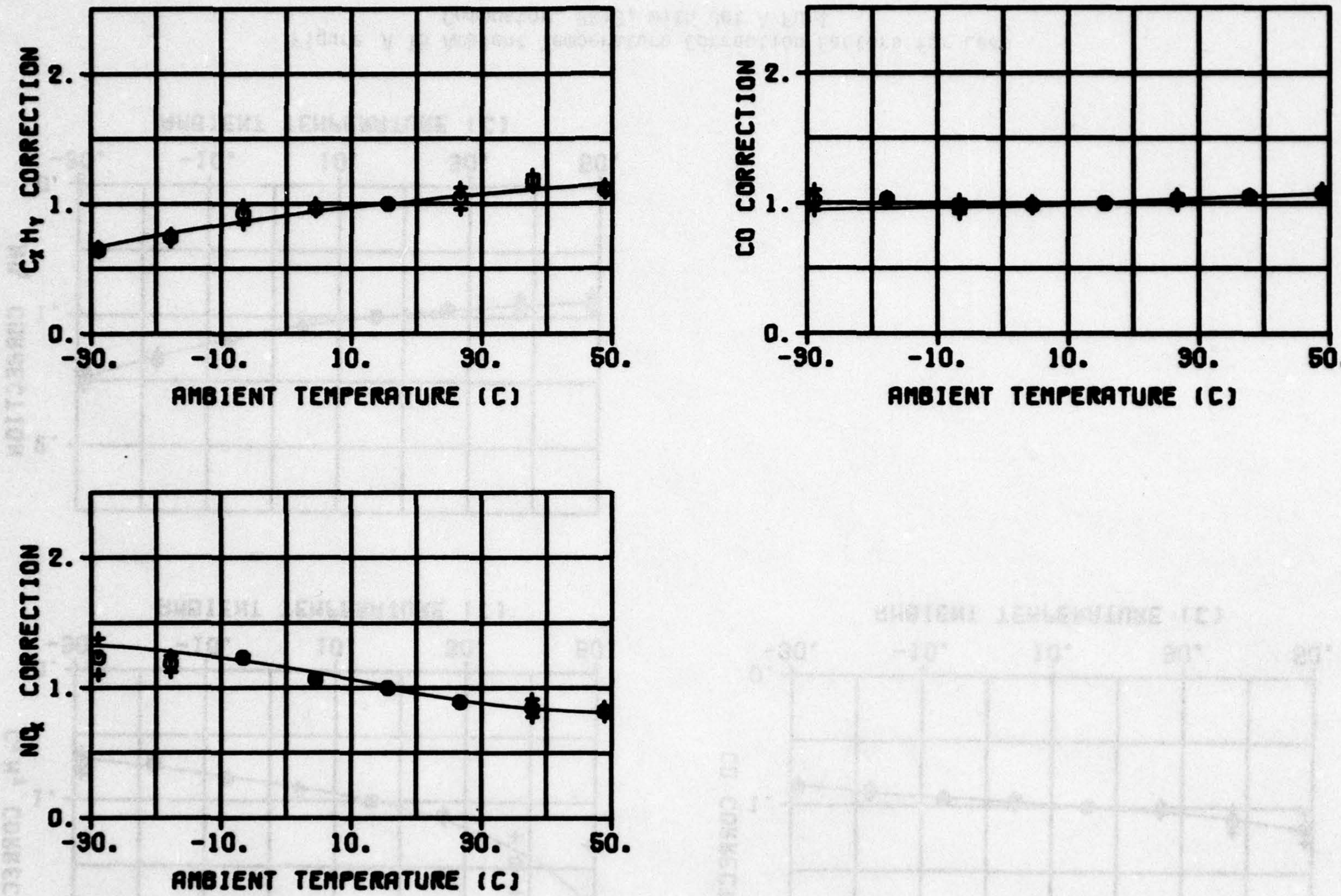

Figure A 14 Ambient Temperature Correction Factors for Lean Combustor, PR=2, with Jet A Fuel

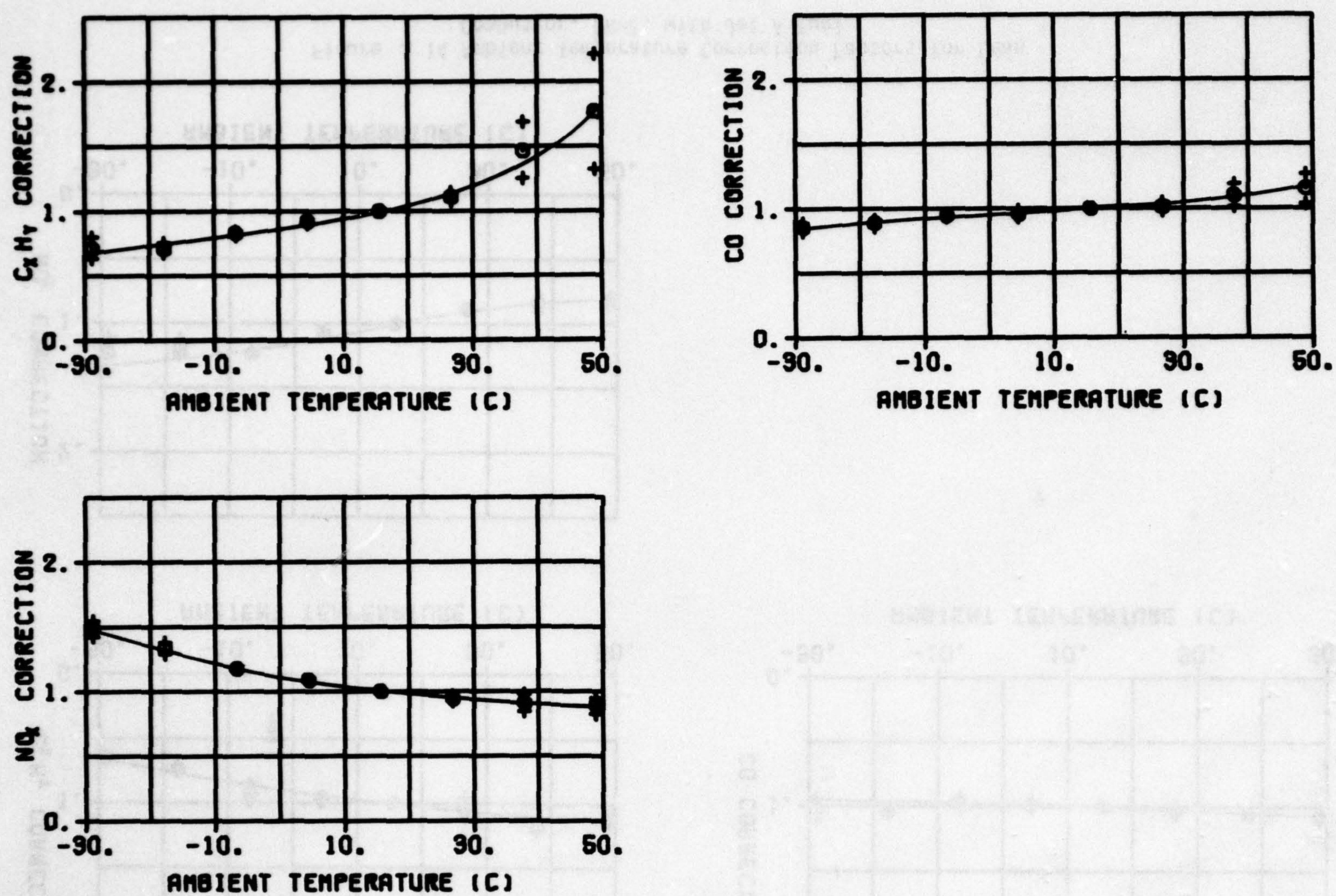

Figure A 15 Ambient Temperature Correction Factors for Lean Combustor, PR=3, with Jet A Fuel

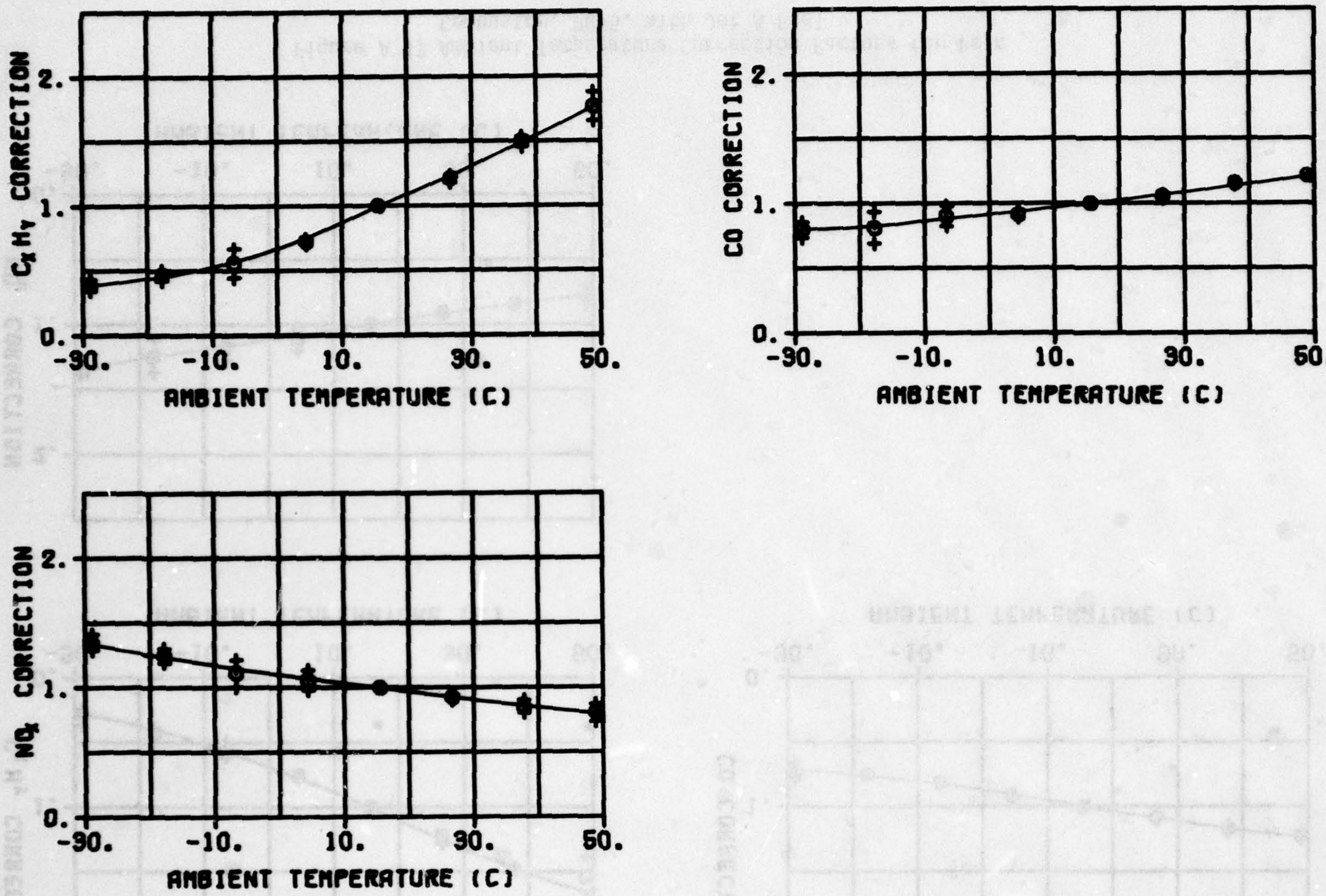

Figure A 16 Ambient Temperature Correction Factors for Lean Combustor, PR=4, with Jet A Fuel

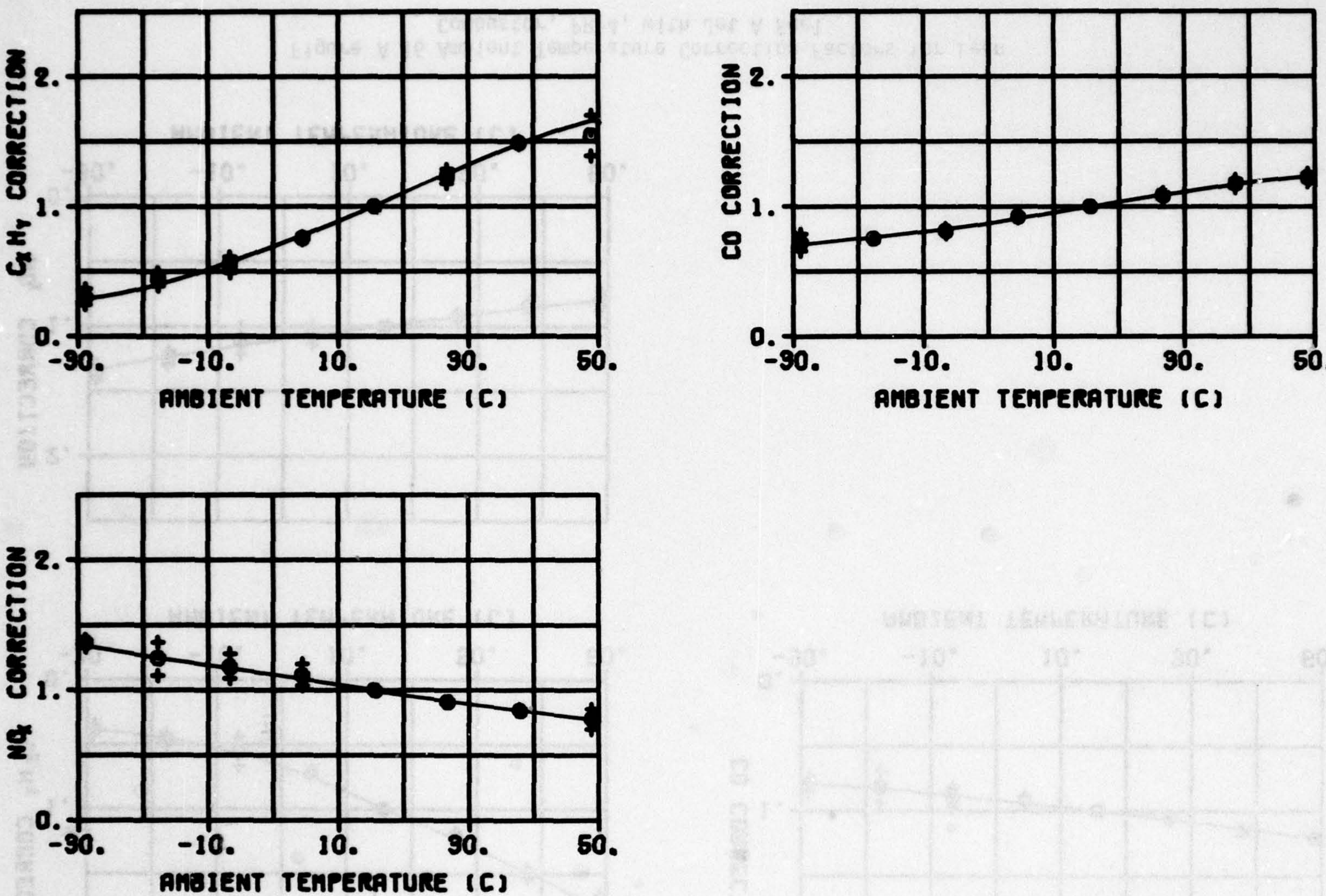

Figure A 17 Ambient Temperature Correction Factors for Lean Combustor, PR=5, with Jet A Fuel

APPENDIX B

AMBIENT PRESSURE CORRECTION FACTORS

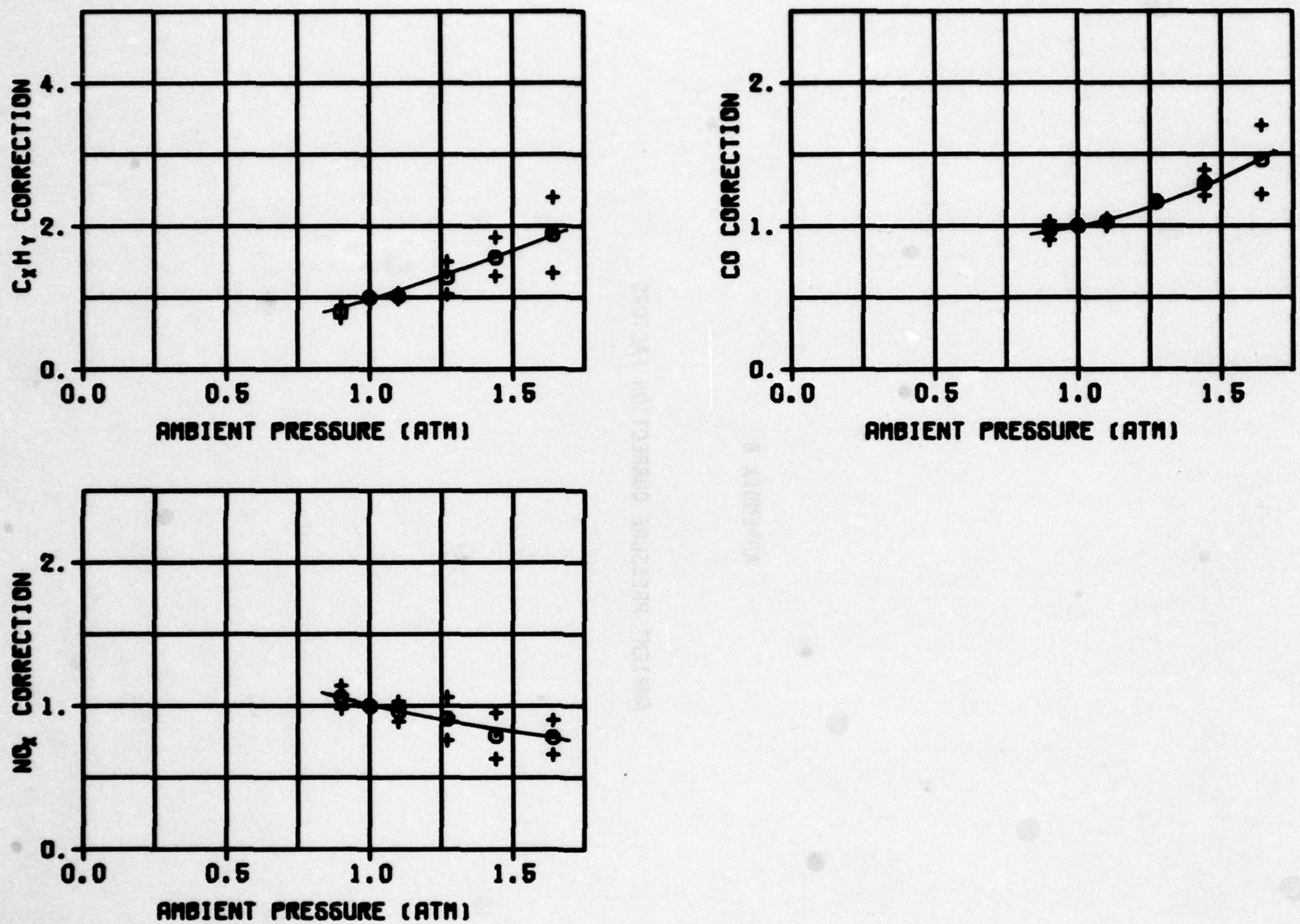

Figure B 1 Ambient Pressure Correction Factors for Standard Combustor, T3=366^{o}K, with JP-4 Fuel

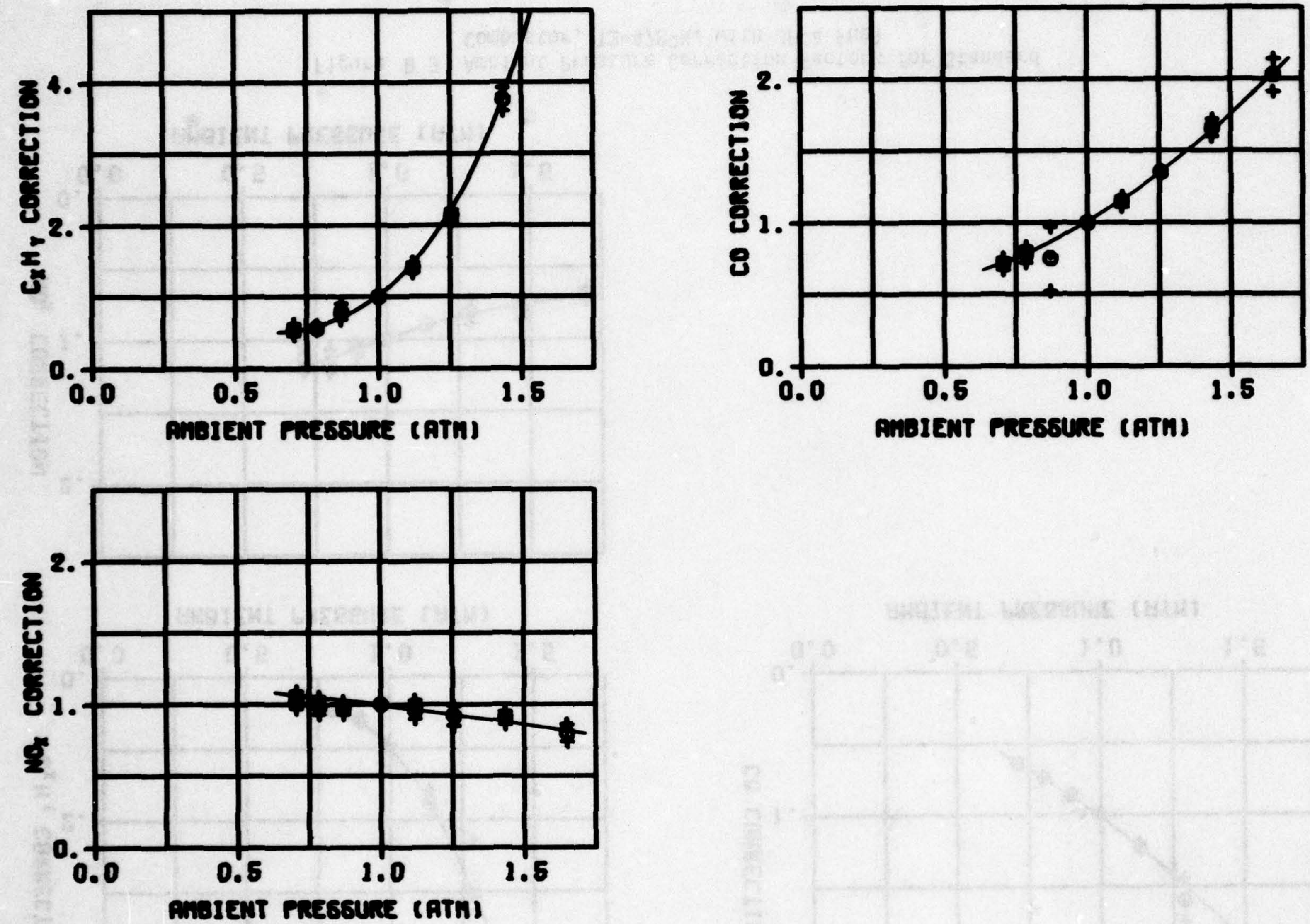

Figure B 2 Ambient Pressure Correction Factors for Standard Combustor, T3=436^{o}K, with JP-4 Fuel

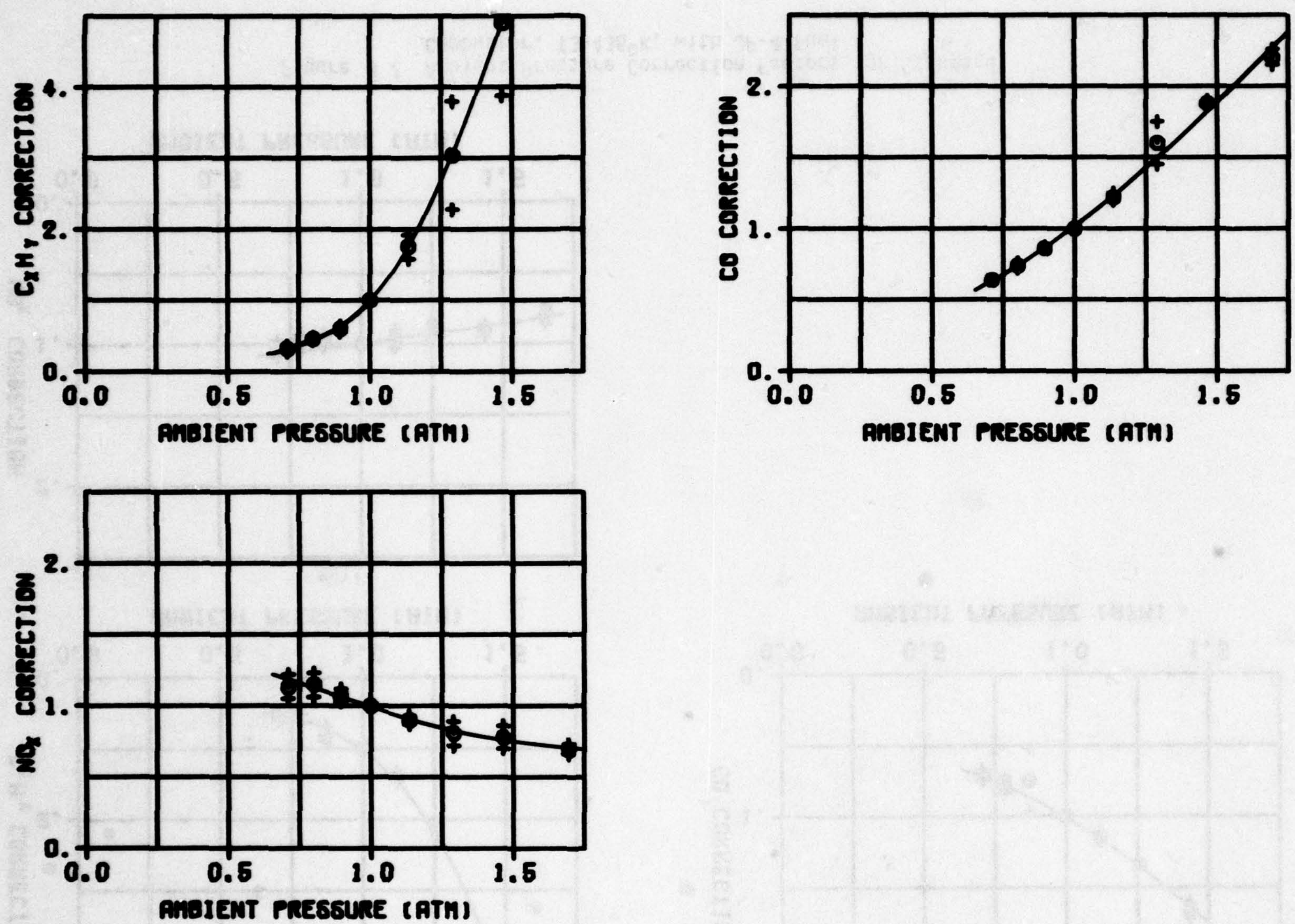

Figure B 3 Ambient Pressure Correction Factors for Standard Combustor, T3=478°K, with JP-4 Fuel

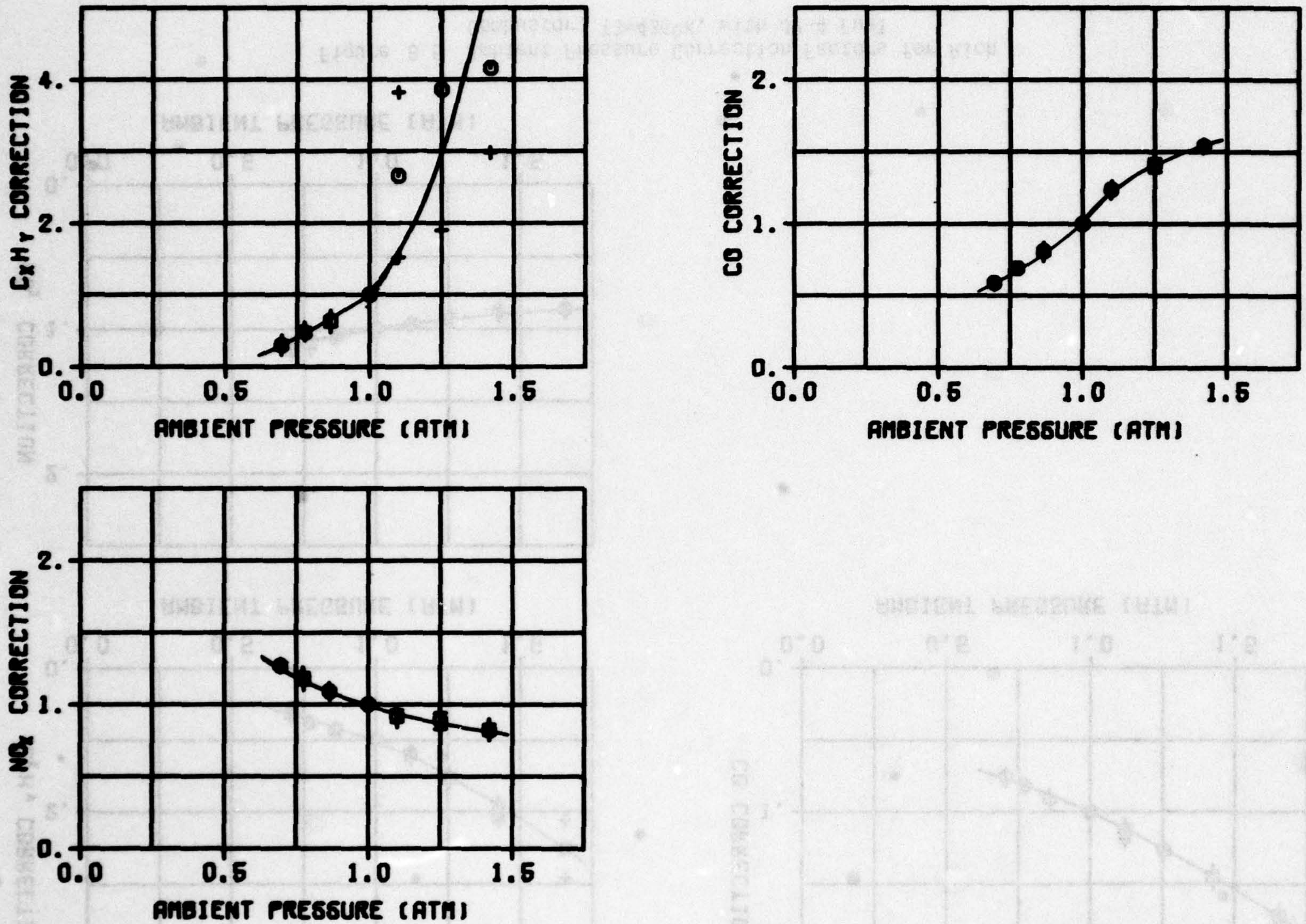

Figure B 4 Ambient Pressure Correction Factors for Standard Combustor, T3=505^{O}K, with JP-4 Fuel

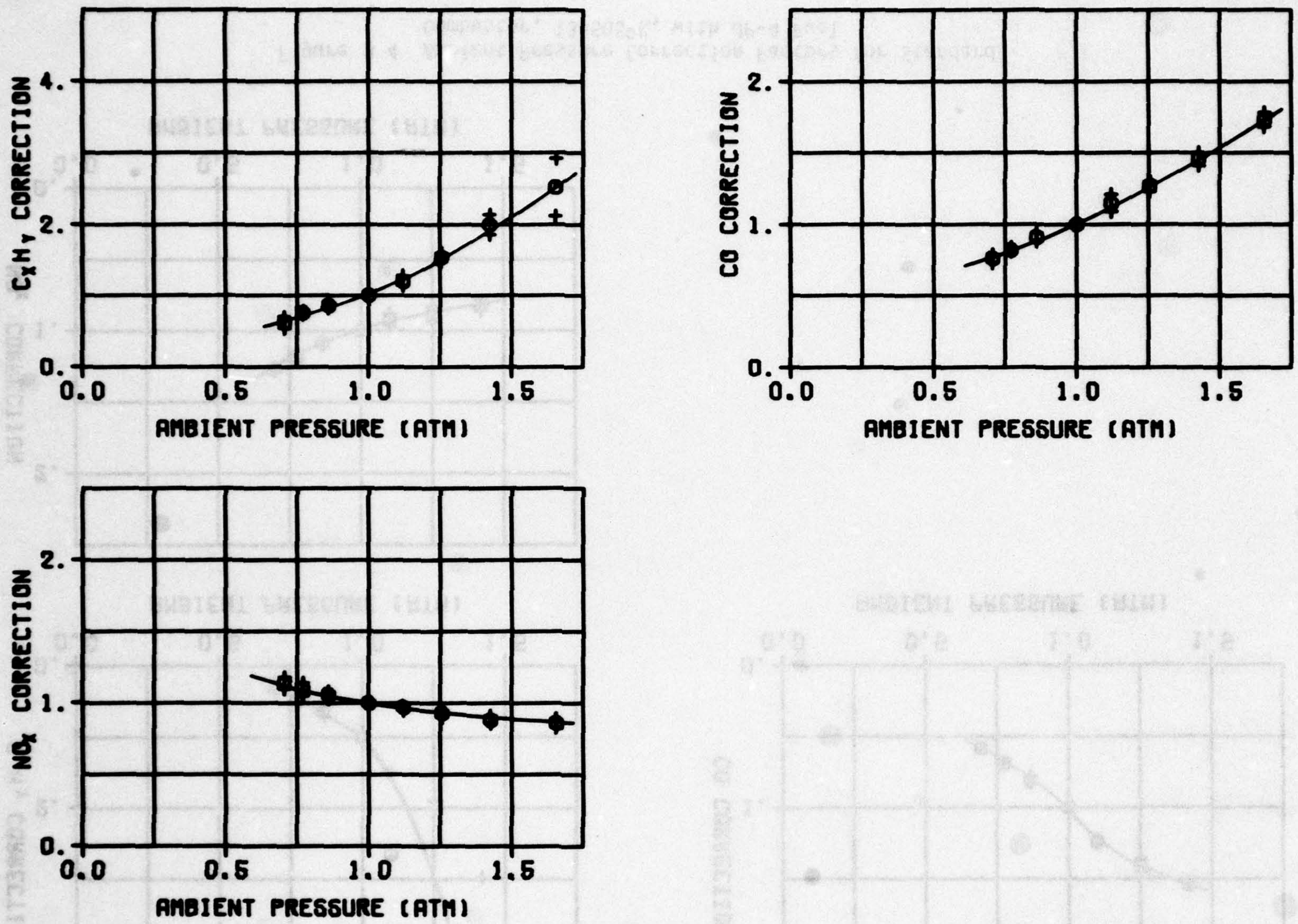

Figure B 5 Ambient Pressure Correction Factors for Rich Combustor, T3=436°K, with JP-4 Fuel

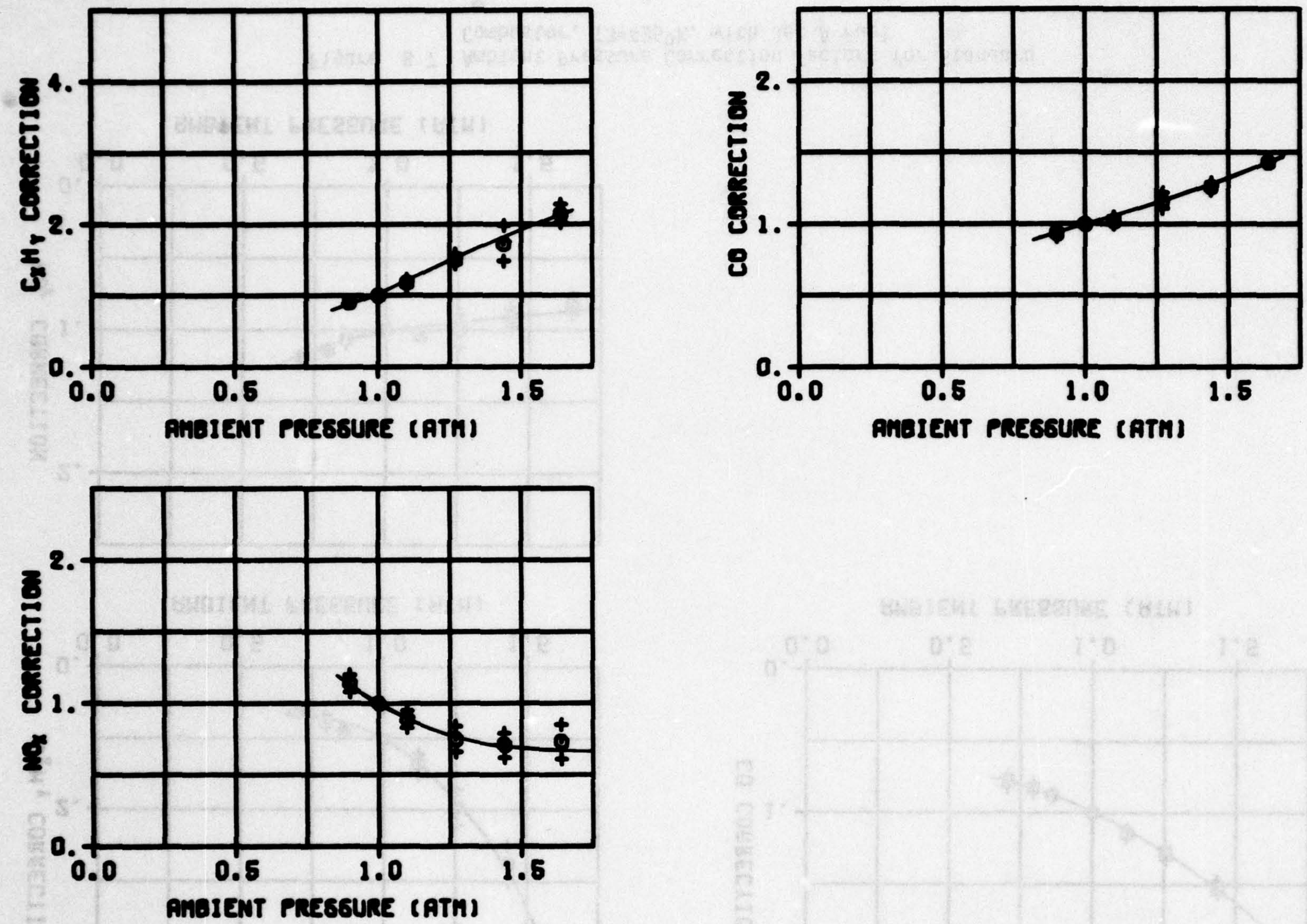

Figure B 6 Ambient Pressure Correction Factors for Standard Combustor, T3=366^{o}K, with Jet A Fuel

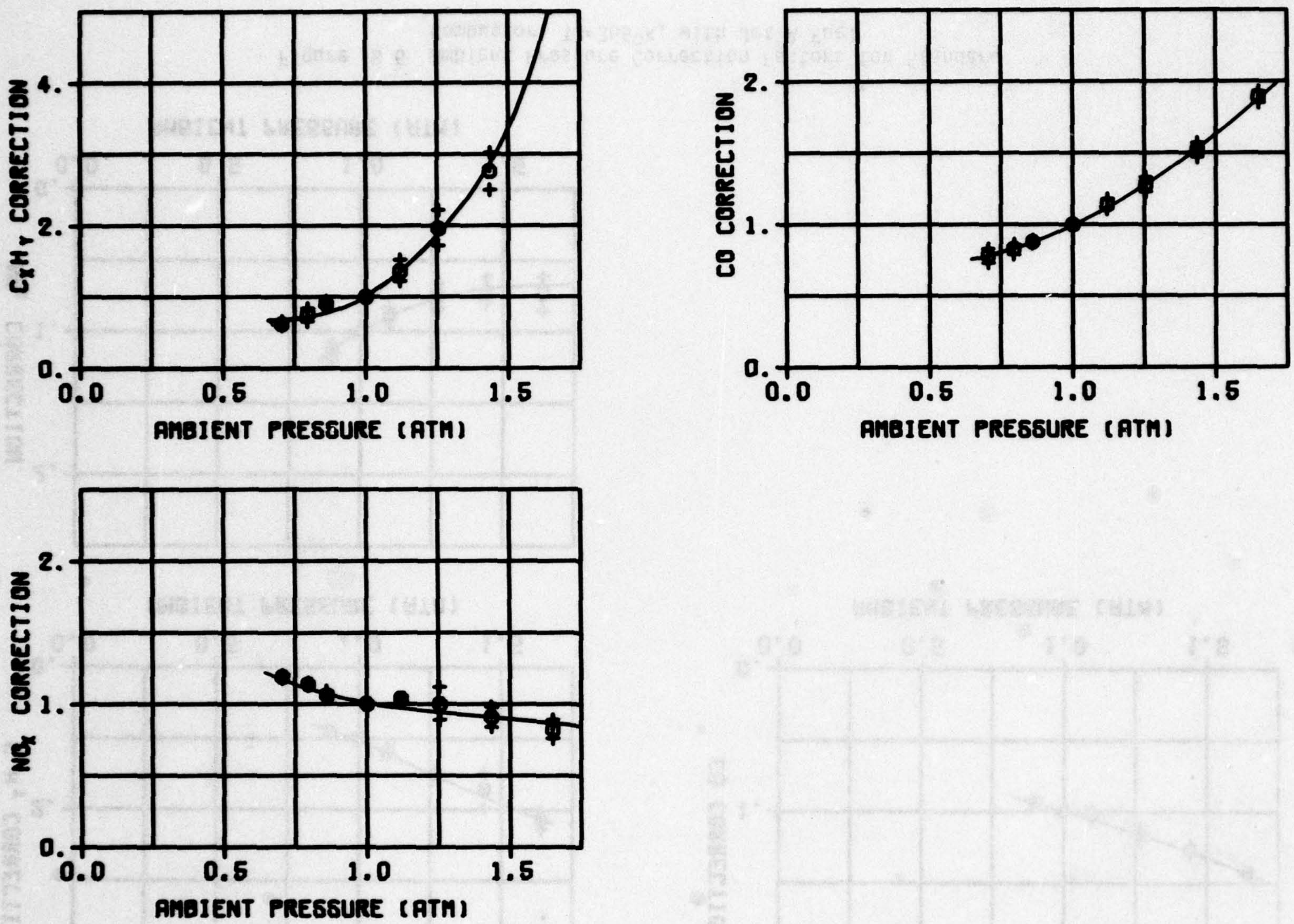

Figure B 7 Ambient Pressure Correction Factors for Standard Combustor, T3=436°K, with Jet A Fuel

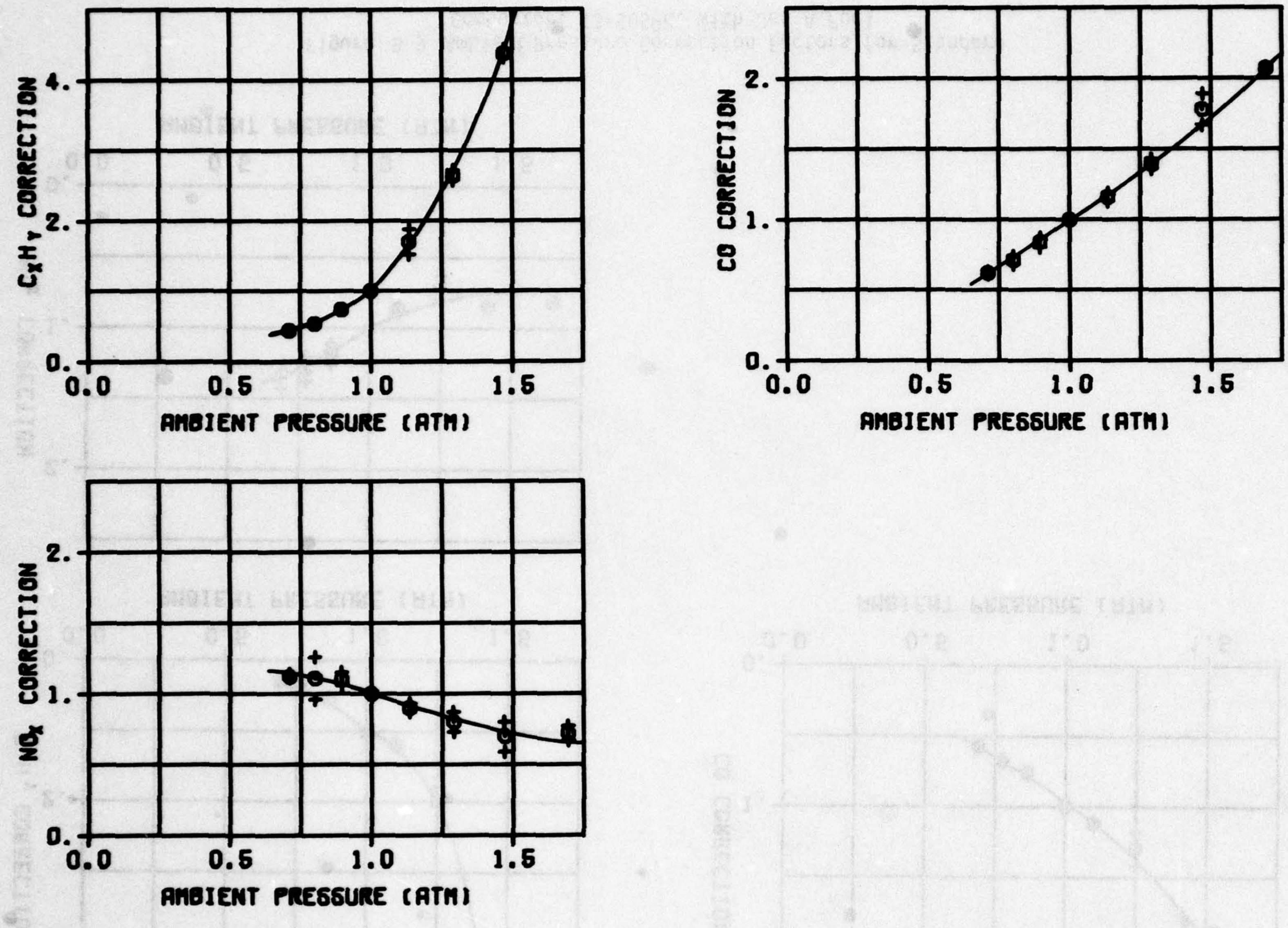

Figure B 8 Ambient Pressure Correction Factors for Standard Combustor, T3=478°K, with Jet A Fuel

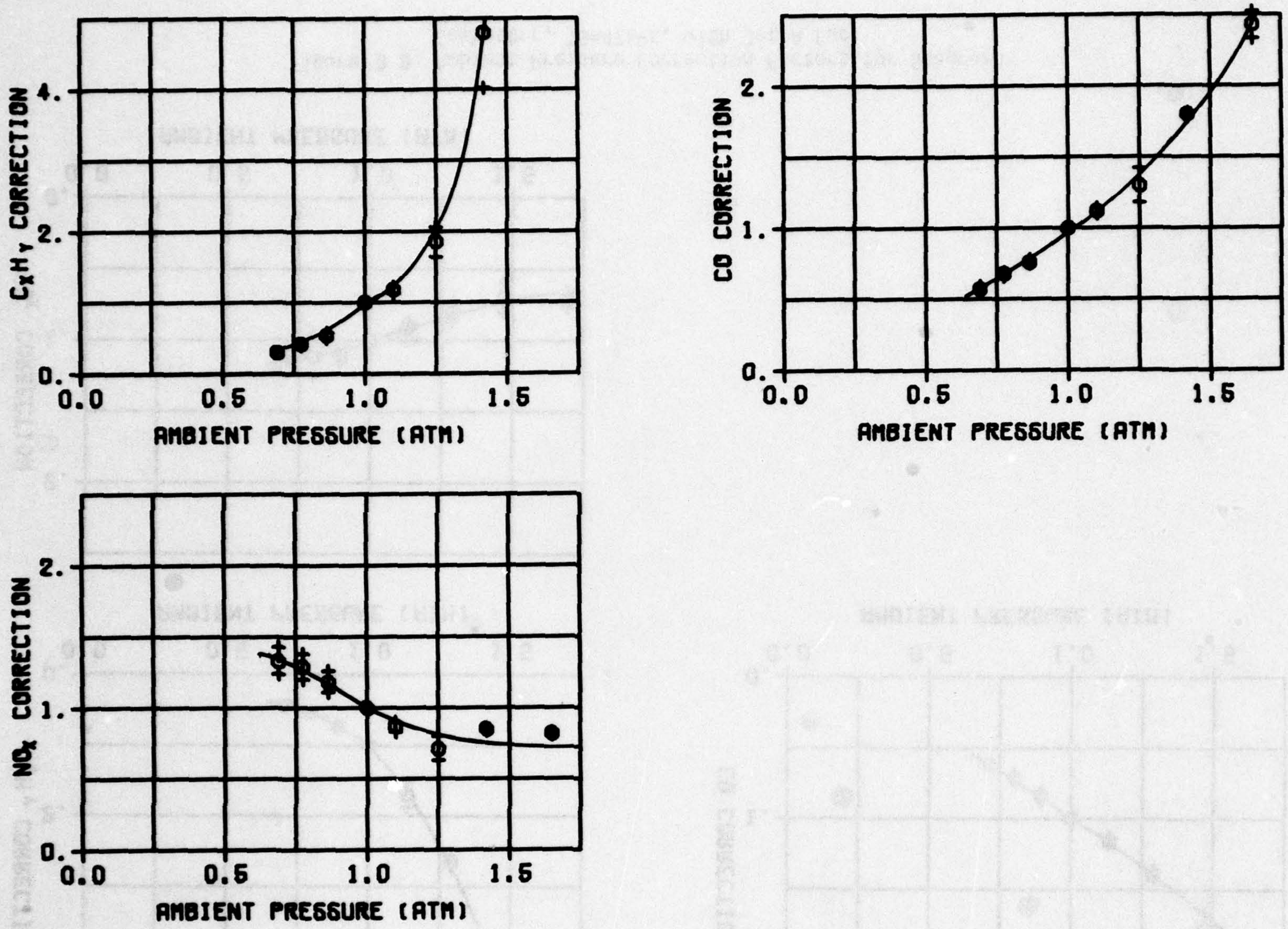

Figure B 9 Ambient Pressure Correction Factors for Standard Combustor, T3=505°K, with Jet A Fuel

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